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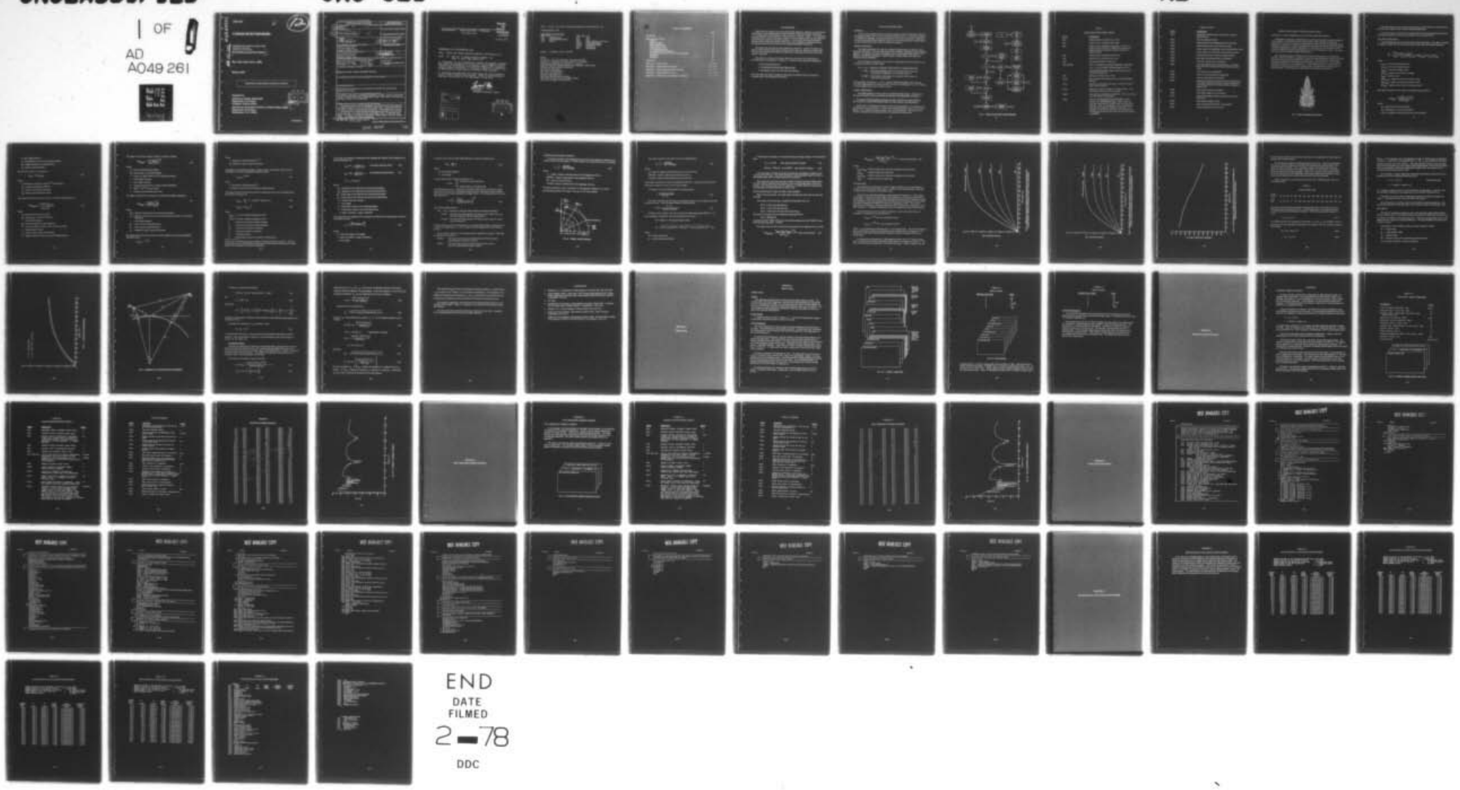

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A RADAR DETECTION MODEL

CENTER FOR NAVAL ANALYSES
1401 Wilson Boulevard
Arlington, Virginia 22209
SYSTEMS EVALUATION GROUP

By: LCdr Kerry Kirk, USN

March 1977

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This paper presents a FORTRAN language radar detection model that determines the signal-to-noise (S/N) ratio as a function of target range. The model determines S/N ratios in a clear or noise jamming environment. The jamming may be created by a self-screening or standoff jammer operating against the radar in the main-lobe and/or side-lobe. The threats may have an ascending, level, or descending flight profile. The effects of atmospheric attenuation, weather clutter, sea state, surface clutter, and multipath may also be considered.

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INTRODUCTION

Radar detection models vary from simple models (page 20, reference 1) with minimal refinements to more sophisticated models (reference 2) with many effects considered, e.g., atmospheric, earth's surface, target, receiver, operator, clutter. It is reasonable to expect that with more refinements, a model can more closely predict the real signal-to-noise (S/N) ratio under the assumed conditions. It is felt that the primary difference between model predictions and fleet results lies in the modeling accomplished between the determination of the S/N ratio and the resultant probability of detection.

This paper does not delve into the probability of detection. Instead, the paper presents a radar detection model that calculates the S/N ratio as a function of target range. The user must decide what techniques to apply when converting the S/N ratio to the probability of detection.

The model is a revision of the radar detection model from the "Countering the Anti-Ship Missile (CAM) Study," reference 3. There are three additional capabilities:

- Self-screening jammers
- Ascending/descending target flight profiles
- Simultaneous main-lobe and side-lobe jamming.

The CAM model was further refined by improving the methods used to calculate the multipath effect and atmospheric attenuation.

RADAR DETECTION MODEL

GENERAL

A macro flow diagram of the revised radar detection model is presented in figure 1. The required inputs to the model are briefly discussed in table 1. The detection model, in FORTRAN IV language, is located in appendix D with user instructions in appendix A. A standoff jamming example (appendix B) and a self-screening jamming example (appendix C) are provided to assist users in running the program.

MODEL STRENGTHS

The model determines S/N ratio as a function of target range in a clear or noise jamming environment. The noise jamming may be created by a standoff or self-screening jammer. The threats may have an ascending, level, or descending flight profile. The effects of atmospheric attenuation, weather clutter, surface clutter, sea state, and multipath may be considered.

In the multipath calculations, the model has a significantly improved method of calculating the reflected ray path length.

The α and β ranges are commonly used measures of radar performance:

α range -- the detection range against a one square meter target with a one watt per megahertz self-screening jammer.

β range -- the detection range against a one square meter target in a clear ECM environment.

The model can calculate the α and β ranges to provide the analyst with a test that the radar being examined is being modeled correctly by comparing the α and β ranges to values obtained from other reliable sources.

MODEL WEAKNESSES

The model calculates the S/N ratio as a function of target range. Then the user must convert the S/N ratio to probability of detection using appropriate techniques.

The targets must be opening or closing the radar's location on a radial bearing. The model does not allow for an offset radar site that produces crossing targets.

Refractivity, the bending of the radar waves by the atmosphere, is accounted for by modifying the radius of the earth. The amount of refraction may be varied, but special effects - e.g., surface ducting, layering - may not be considered. The amount of refraction is programmed using input X(15): the coefficient of refractivity.

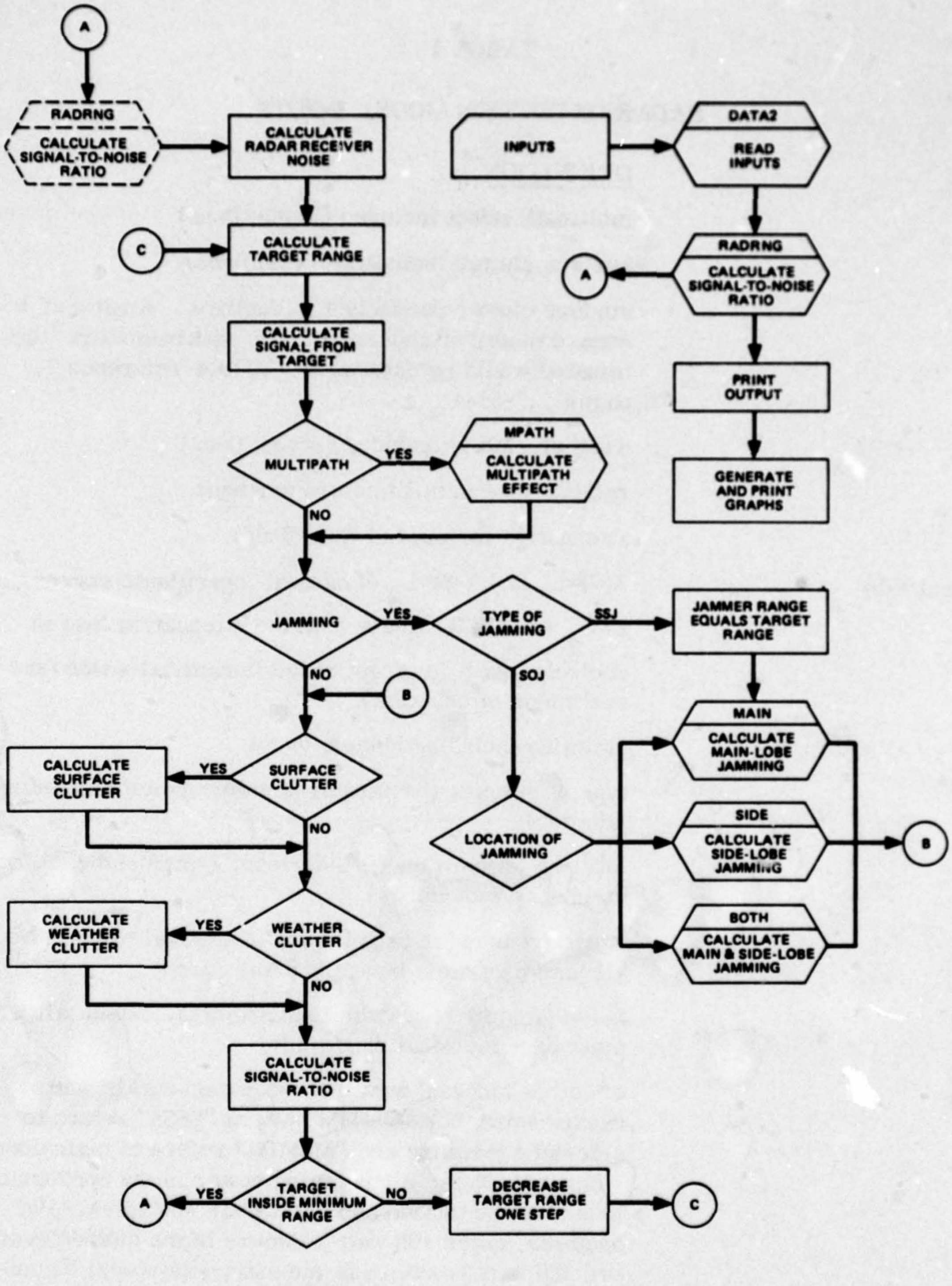

FIG. 1: RADAR DETECTION FLOW DIAGRAM

TABLE 1

RADAR DETECTION MODEL INPUTS

INPUT	DEFINITION
X(1)	multipath effect included (1=yes; 0=no)
X(2)	surface clutter included (1=yes; 0=no)
X(3)	surface clutter coefficient in decibels. A ratio of 1 square meter of clutter to 1,000 square meters illuminated would be entered as -30 (see reference 1, pages 527-534)
X(4)	weather clutter included (1=yes; 0=no)
X(5)	rainfall rate in millimeters per hour
X(6)	attenuation included (1=yes; 0=no)
X(7) and X(8)	$X(7)=L_1$ and $X(8)=L_2$ of natural logarithmic regression $L=L_1 + L_2 \, LnR$, where L is the attenuation loss in decibels and R is target range in nautical miles (see section on attenuation)
X(9)	jamming including (1=yes; 0=no)
X(10)	type of jammer (0=standoff jammer; 1=self-screening jammer)
X(11)	location of jamming (0=side-lobe; 1=main-lobe; 2=both main- and side-lobes)
X(12)	range from radar to jammers in nautical miles. Note: all jammers must be at the same range
X(13)	noise jammer bandwidth in megahertz. Note: all jammers must have identical bandwidths
X(14)	effective radiated power of the jammer(s) in watts. Packed word "SSSSMMMM" where "SSSS" refers to side-lobe jamming and "MMMM" refers to main-lobe jamming. Note: all jamming power in the appropriate lobe must be totaled and entered as one value. For example, three 100 watt jammers in the side-lobe and two 100 watt jammers in the main-lobe would be entered as 03000200

TABLE 1 (Cont'd)

INPUT	DEFINITION
X(15)	coefficient of refractivity (1.333 for the 4/3 earth approximation)
X(16)	sea state (Beaufort scale)
X(17)	target altitude at the beginning of the run (in feet)
X(18)	target altitude at the end of the run (in feet)
X(19)	target range at the beginning of the run (in nautical miles)
X(20)	target range at the end of the run (in nautical miles)
X(21)	average target cross section (in square meters)
X(22)	peak radar transmitted power (in kilowatts)
X(23)	main-lobe antenna gain (in decibels)
X(24)	side-lobe antenna gain (in decibels) (e.g., side-lobe down 25 db from the main-lobe gain would be entered as 25)
X(25)	radar frequency (in megahertz)
X(26)	receiver noise bandwidth (in megahertz)
X(27)	receiver noise figure (in decibels)
X(28)	integration improvement in S/N ratio (in decibels) (e.g., if the radar integrates 100 pulses, perfect integration improvement would be entered as 20) (see reference 1, pages 35-40)
X(29)	radar system losses (in decibels)
X(30)	radar pulse length (in microseconds)
X(31)	azimuth beamwidth in degrees measured at the 3 db down level
X(32)	radar antenna height (in feet)
X(33)	radar polarization (0=vertical; 1=horizontal)
X(34)	output in graph form (1=yes; 0=no)

Effective Earth's Radius = X(15) times earth's radius

Using X(15) = 1.333 corresponds to the nominal 4/3 earth approximation.

Atmospheric attenuation, the absorption of a portion of the radar's signal strength by the atmosphere, will be discussed in a later section. The technique this detection model uses to calculate the amount of attenuation was determined from attenuation curves contained in reference 5. These attenuation curves assume the Central Radio Propagation Laboratory exponential reference atmosphere for refraction and the International Civil Aviation Organization standard atmosphere for pressure-temperature values. The detection model cannot consider irregular atmospheres.

Noise jamming signals are enhanced by the radar's antenna gain on the jamming bearing. Figure 2 presents an example of a radar antenna gain pattern with the main-lobe and various side-lobes described by the shaded area. This model uses a single value (averaged throughout the side-lobes) for antenna gain in the side-lobes. This method is represented in figure 2 by the dashed line. A closer approximation to reality could be achieved by allowing the jammers to operate against the antenna gain averaged over a smaller region. This technique is represented by the dotted line in figure 2.

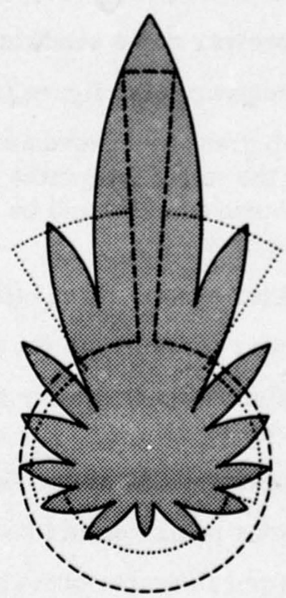

FIG. 2: SAMPLE ANTENNA GAIN PATTERN

The model requires that all the standoff jammers, both in the main- and side-lobes, be at the same range and have identical jamming bandwidths.

The model does not consider the multipath effects of the jamming signal interfering with itself, nor does it allow for the movement of the jamming vehicle.

CAM DETECTION MODEL

The CAM detection model is the basis for this revised model. The model calculates the signal-to-noise ratio as a function of target range using the following equations:

$$\frac{S}{N} = \frac{SIG_{TAR}\, F_{MUL2}\, F_{ATT2}}{N_{REC} + F_{ATT2}\,(SIG_{SCLTR} + SIG_{WTHR}) + F_{ATT1}\, SIG_{JAM}} \tag{1}$$

where:

F_{ATT1} = one-way attenuation factor

F_{ATT2} = two-way attenuation factor

F_{MUL2} = two-way multipath effect

SIG_{TAR} = signal received from the target

N_{REC} = receiver noise

SIG_{SCLTR} = signal received from surface clutter

SIG_{WTHR} = signal received from weather clutter

SIG_{JAM} = signal received from the jamming source

The signal received from the target is calculated using equation 2:

$$SIG_{TAR} = \frac{P_T G_T^2 n\epsilon_i(n) \lambda^2 \sigma_t}{(4\pi)^3 L_S R_T^4} \tag{2}$$

where:

P_T = peak transmitted power (watts)

G_T = antenna gain, main-lobe (decibels)

$n\epsilon_i$ (n) = integration improvement in S/N ratio (decibels)

λ = wave length (meters)

σ_t = average target cross section (square meters)

R_T = range from radar to target (meters)

L_S = system losses (decibels)

The receiver noise is as in equation 3:

$$N_{REC} = K\,T_O F_N B_N \tag{3}$$

where:

K = Boltzmann's constant ($1.38 X 10^{-23}$ Joules/degree)

T_O = standard temperature (290^{o} K)

F_N = receiver noise figure (decibels)

B_N = receiver noise bandwidth (hertz)

The signal received from surface clutter is calculated using equation 4:

$$SIG_{SCLTR} = \frac{P_T G_T^2 \lambda^2 B_Z C \tau \sigma_O}{2\,(4\pi)^3 R^3} \tag{4}$$

where:

P_T = peak transmitted power (watts)

G_T = antenna gain, main-lobe (decibels)

λ = wave length (meters)

B_Z = azimuth bandwidth of radar (degrees)

C = velocity of light (2.997925×10^8 meters per second)

τ = pulse length (seconds)

σ_o = surface clutter coefficient (decibels)

R = range at which S/N ratio is being calculated (meters)

The signal received from weather clutter is written as follows:

$$SIG_{WTHR} = \frac{.93\ P_T G_T C \tau \pi^4 Z}{128\ \lambda^2\ R^2} \tag{5}$$

where:

P_T = peak transmitted power (watts)

G_T = antenna gain, main-lobe (decibels)

C = velocity of light (2.997925×10^8 meters per second)

τ = pulse length (seconds)

λ = wave length (meters)

R = range at which S/N ratio is being calculated (meters)

Z = $200\ r^{1.6}\ (10^{-18})$ (cubic meters)

r = rainfall rate (millimeters per hour)

The signal received from the jammer is calculated according to equation 6:

$$SIG_{JAM} = \frac{P_J G_J G'_T\ \lambda^2 B_N}{(4\pi)^2\ B_J R_J^2} \tag{6}$$

where:

$P_J G_J$ = effective radiated power of noise jammer (watts)

G'_T = effective radar gain in the direction of the jammer (main- or side-lobe) (decibels)

λ = wave length (meters)

B_N = receiver noise bandwidth (hertz)

B_J = noise jammer bandwidth (hertz)

R_J = range from radar to jammer (meters)

The signal received from the jammer must be modified by a one-way atmospheric attenuation factor:

$$F_{ATT} = e^{-\alpha R_J} \tag{7}$$

where:

α = attenuation coefficient (meters^{-1}) [1]

R_J = range from radar to jammer (meters)

The signals received from the target, surface clutter, and weather clutter must be modified by a two-way atmospheric attenuation factor:

$$F_{ATT2} = e^{-2\alpha R} \qquad (8)$$

where:

α = attenuation coefficient (meters^{-1})

R = range at which S/N ratio is being calculated (meters)

The signal received from the target must be modified by the two-way multipath propagation factor (reference 4):

$$F_{MUL1} = \frac{P}{P_O} = 1 + (R_C \rho D)^2 + 2R_C \rho D \cos \phi \qquad (9a)$$

$$F_{MUL2} = (F_{MUL1})^2 \qquad (9b)$$

where:

F_{MUL1} = one-way multipath propagation factor

F_{MUL2} = two-way multipath propagation factor

P = power at the target including multipath

P_O = power at the target excluding multipath

R_C = smooth sea reflection coefficient

ρ = rough sea reflection coefficient

D = divergence factor

ϕ = phase angle of direct ray relative to reflected ray

[1]There are two common uses of the symbol "α" within the radar community. The first usage refers to the 1 $W/MHZ/M^2$ self-screening jammer detection range and the second refers to the atmospheric attenuation coefficient.

The smooth sea reflection coeffiecient of the reflected ray relative to the incident ray is given by (reference 4):

$$R_V e^{-j\phi_v} = \frac{n \sin \Psi - 1}{n \sin \Psi + 1} \quad \text{(vertically polarized radar)} \quad (10)$$

$$R_H e^{-j\phi_h} = \frac{\sin \Psi - n}{\sin \Psi + n} \quad \text{(horizontally polarized radar)} \quad (11)$$

$$n^2 = \epsilon_1 - (18.3\sigma\lambda)\, j$$

where:

R_V = magnitude of the reflected ray (vertical polarization)

R_H = magnitude of the reflected ray (horizontal polarization)

ϕ_v = phase angle of the reflected ray (vertical polarization)

ϕ_h = phase angle of the reflected ray (horizontal polarization)

n = complex dielectric constant

λ = wave length

ϵ_1 = permitivity constant of the reflecting surface

σ = conductivity constant of the reflecting surface

Ψ = angle of incidence = angle of reflection

For rough seas, the magnitude of the reflected ray relative to the incident ray is given by (references 4 and 5):

$$\rho = e^{-\left[8\left(\frac{\pi h \sin \Psi}{\lambda}\right)^2\right]} \quad (12)$$

where:

h = root-mean-square wave height

Ψ = angle of incidence = angle of reflection

λ = wave length

The phase shift caused by path length difference is given by (reference 2):

$$\phi_\delta = \frac{\Delta R}{\lambda} 2\pi \tag{13}$$

where:

ΔR = path length difference
λ = wave length

The total phase angle is given by (reference 4):

$$\phi = \phi_\delta - \begin{cases} \phi_v & \text{(vertical polarization)} \\ \text{or} & \\ \phi_h & \text{(horizontal polarization)} \end{cases} \tag{14}$$

The divergence factor is a result of the ray being reflected from a spherical surface rather than a flat surface. Divergence spreads the ray, reducing the signal strength per unit area; and thereby reducing the multipath effect. The divergence factor is given by (reference 4):

$$D = \left[1 + \frac{2R_1R_2}{R_e(R_1+R_2)\sin\Psi} \right]^{-\frac{1}{2}} \tag{15}$$

SELF-SCREENING JAMMER

The α and β ranges are commonly used measures of radar performance:

α range -- The detection range against a one square meter target with a one watt per megahertz self-screening jammer.

β range -- The detection range against a one square meter target in a clear ECM environment.

A radar detection model can demonstrate to the analyst that the radar is being modeled correctly by comparing the α and β ranges to values obtained from other reliable sources.

By use of input "X(10)," a self-screening jammer capability is treated. This input is programmed such that, if:

X(10)=0 The model would accept a standoff jammer with the jammer's range being the value input as X(12)

X(10)=1 The model would accept a self-screening jammer with the jammer's range being the target's range

ASCENDING/DESCENDING TARGETS

The target's position at the beginning and end of the run is entered in relation to the surface of the earth (see figure 3). These positions are converted into polar coordinates.

$$\Omega_1 = \frac{\pi}{2} - \frac{RNGBGN}{RE + ALTBGN} \tag{16}$$

where:

Ω_1 = target's angular (radians) position at the beginning of the run

RNGBGN = target's range (feet) at the beginning of the run

RE = radius of the earth (feet)

ALTBGN = target's altitude (feet) at the beginning of the run

The target's position in polar coordinates at the beginning is (PREALT, Ω_1) where present altitude (PREALT) is equal to the sum of RE and ALTBGN.

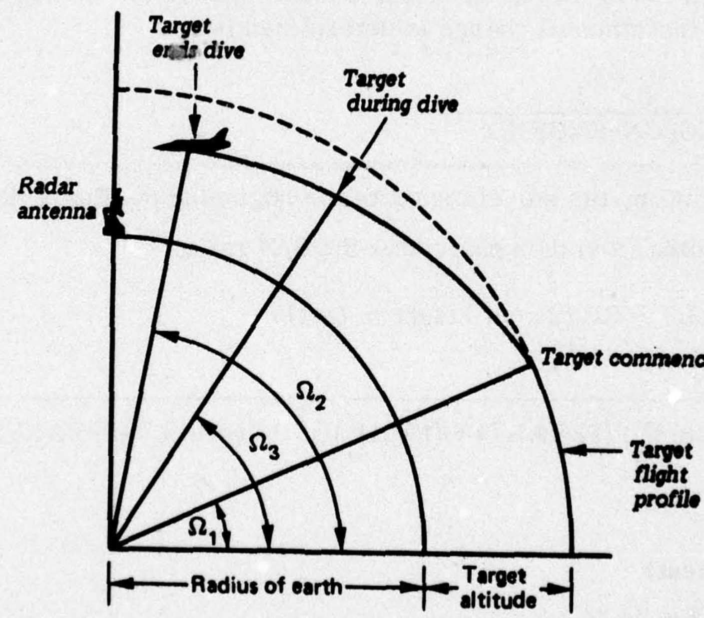

FIG. 3: TARGET FLIGHT PROFILE

The target's position at the end of the run is determined by:

$$\Omega_2 = \frac{\pi}{2} - \frac{RNGEND}{RE + ALTEND} \qquad (17)$$

where:

Ω_2 = target's angular position (radians) at the end of the run

RNGEND = target's range (feet) at the end of the run

ALTEND = target's altitude (feet) at the end of the run

The target's end position in polar coordinates is (FNLALT, Ω_2) where the final altitude (FNLALT) is equal to the sum of RE and ALTEND.

The target's rate of ascent/descent (γ) is determined by:

$$\gamma = \frac{ALTBGN\text{-}ALTEND}{\Omega_2 - \Omega_1} \qquad (18)$$

The model calculates the S/N ratio at incremental ranges from the beginning through the end of the run. The incremental change is determined by:

$$STEP = \frac{\Omega_2 - \Omega_1}{RNGBGN\text{-}RNGEND} \qquad (19)$$

During the first iteration, the model converts the beginning position (PREALT, Ω_1) into rectangular coordinates, and then calculates the S/N ratio.

HT = PREALT - RE (target height in feet)

$$RT = \sqrt{[(\sin \Omega_1)(PREALT) - (RE+H_1)]^2 + [(\cos \Omega_2)(PREALT)]^2} \qquad (20)$$

where:

RT = target range (feet)

H_1 = radar antenna height (feet)

Following this calculation, the model decreases the target range by one incremental step.

$$\Omega_1 = \Omega_1 + STEP \qquad \text{(new angular position of target)} \qquad (21)$$

$$PREALT + PREALT - [(\gamma)(STEP)] \qquad \text{(new altitude of target)} \qquad (22)$$

The model again converts the target's position into rectangular coordinates and calculates the S/N ratio. The model continues to close the target toward the radar in incremental steps until the target reaches its end position.

If the target has more than one rate of ascent or descent during its flight profile, the rates must be separated into individual cases involving single rates of ascent or descent. The model can also allow for targets at a constant altitude by entering both the beginning and ending altitude as the same value.

SIMULTANEOUS MAIN-LOBE AND SIDE-LOBE JAMMING

With a multi-axis threat, one might expect simultaneous main-lobe and side-lobe jamming.

The location of the jamming is programmed using input X(11), if:

X(11) = 0 side-lobe jamming only

X(11) = 1 main-lobe jamming only

X(11) = 2 both main-lobe and side-lobe jamming.

The power of the jammer(s) is programmed using input X(14).

X(14) = SSSSMMMM,

a packed word with "SSSS" referring to side-lobe jamming power and "MMMM" being main-lobe jamming power, in watts.

The signal received from the jammers (see equation 6) is separated into two parts:

$$SIG_{JAM(M)} = \frac{P_{J(M)}\, G_{J(M)}\, G_{T(M)}\, \lambda^2\, B_N}{(4\pi)^2\, B_J\, R_j^2} \quad \text{(main-lobe jamming)} \qquad (23)$$

$$SIG_{JAM\,(S)} = \frac{P_{J(S)}\, G_{J(M)}\, G_{T(S)}\, \lambda^2\, B_N}{(4\pi)^2\, B_J\, R_J^{\,2}} \quad \text{(side-lobe jamming)} \qquad (24)$$

where:

$P_{J(M)}\, G_{J(M)}$ = effective power of all jammers radiating in the main-lobe

$G_{T(M)}$ = effective main-lobe radar gain

$P_{J(S)}\, G_{J(S)}$ = effective power of all jammers radiating in the side-lobe

$G_{T(S)}$ = effective side-lobe radar gain.

ATTENUATION

The atmospheric attenuation of a radar's signal strength in a clear atmosphere is due primarily to oxygen and water vapor. A portion of the radiated energy is absorbed as heat by these atmospheric factors and is lost.

Figures 4 and 5 present attenuation curves taken from reference 5. These curves are treated as a function of target range, radar frequency, and elevation (horizontal to target) angle. These curves were calculated using the Central Radio Propagation Laboratory exponential reference atmosphere for refraction and the International Civil Aviation Organization standard atmosphere for pressure-temperature values. This section describes the technique to calculate attenuation, which is based on the attenuation curves from reference 5. Irregular atmospheres cannot be considered in this detection model.

The CAM detection model, as well as references 1 and 5, treats the effects of atmospheric attenuation by an exponential law.

$$F_{ATT1} = e^{-\alpha R} \quad \text{(one-way attenuation factor)}$$

$$F_{ATT2} = e^{-2\alpha R} \quad \text{(two-way attenuation factor)}$$

where α is the attenuation coefficient and R is the target range. The reader should note that the attenuation coefficient is multiplied by two to obtain two-way attenuation. The attenuation coefficient is determined by dividing the one-way attenuation loss by the target range.

The attenuation coefficients for a 1000 megahertz radar with a 0^o elevation angle were calculated at 20 nautical mile intervals from figure 4 and graphed on figure 6. The curve of the attenuation coefficients is not linear with range. Using a constant value for

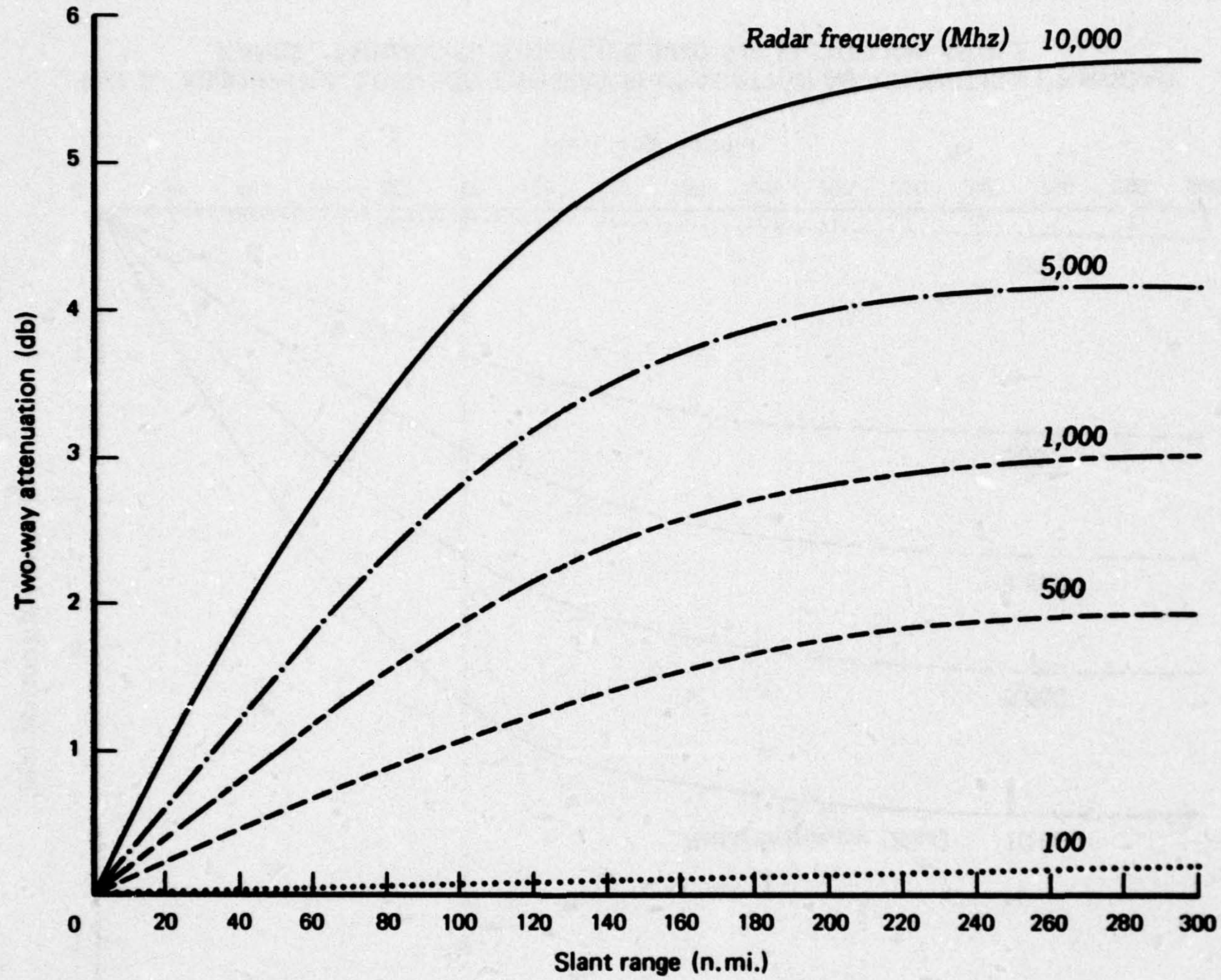

FIG. 4: ABSORPTION LOSS FOR TWO-WAY PROPAGATION AS A FUNCTION OF RADAR RANGE, VARIOUS FREQUENCIES, AND 0° ELEVATION ANGLE

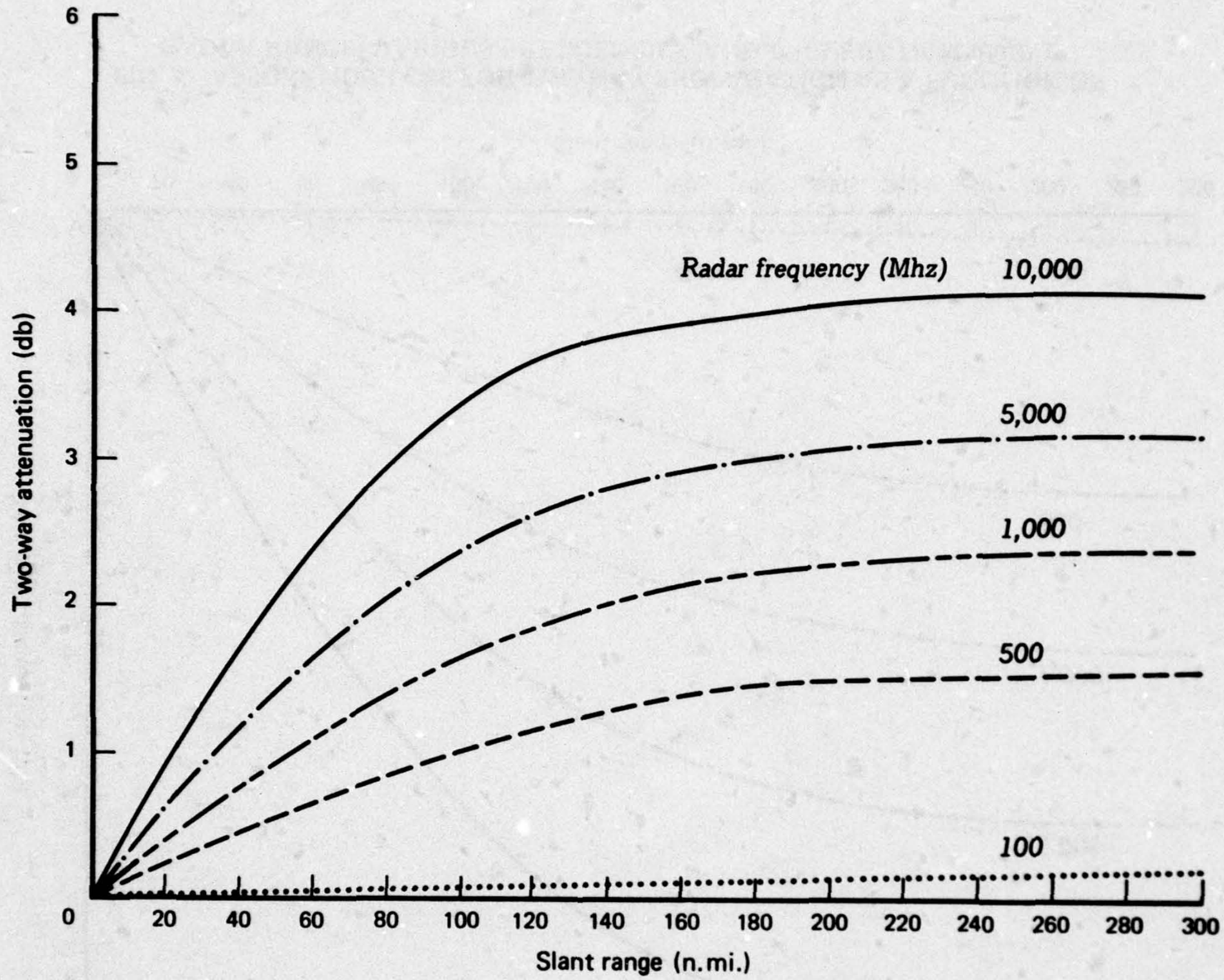

FIG. 5: ABSORPTION LOSS FOR TWO-WAY PROPAGATION AS A FUNCTION OF RADAR RANGE, VARIOUS FREQUENCIES, AND 0.5° ELEVATION ANGLE

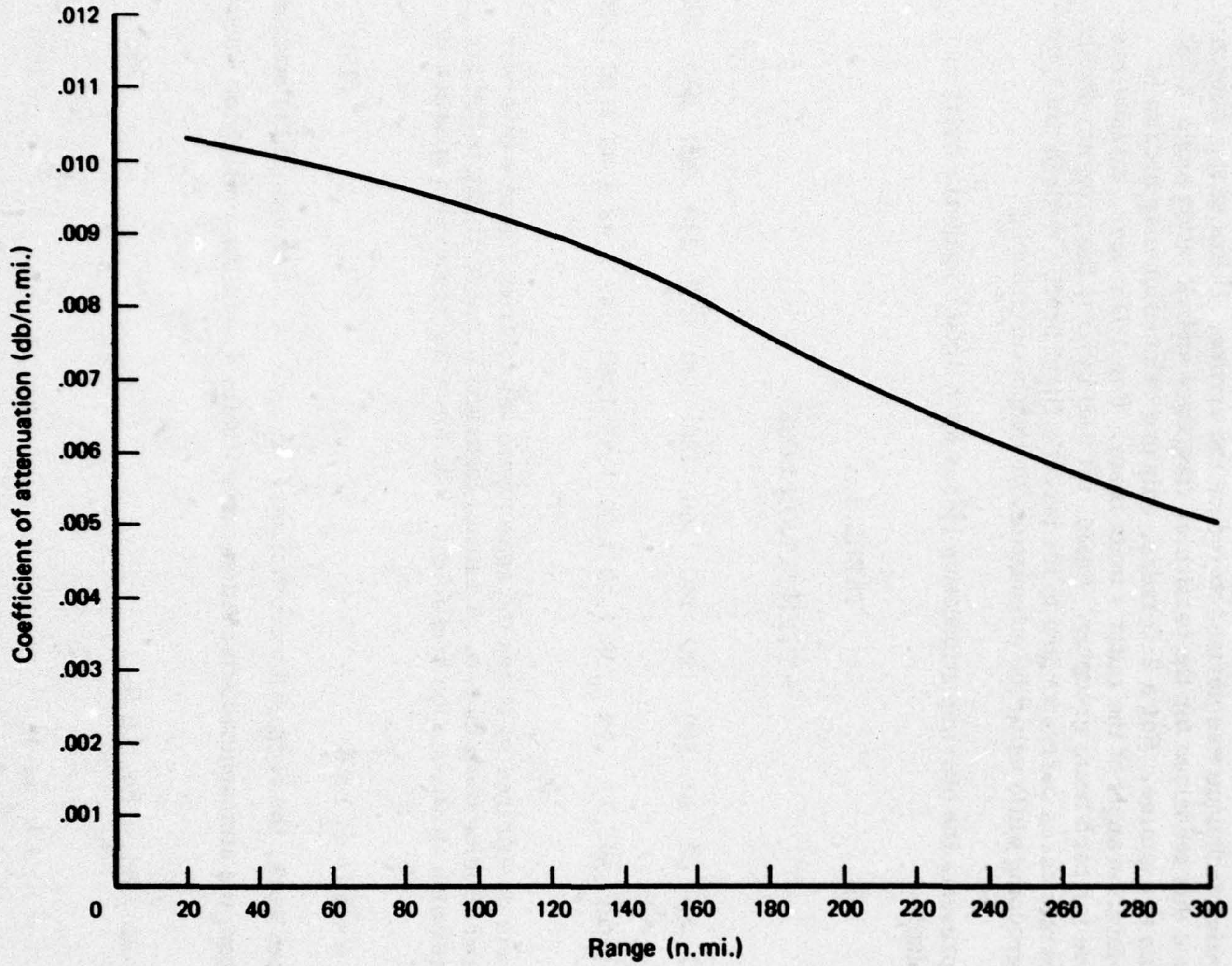

FIG. 6: COEFFICIENT OF ATTENUATION FOR A RADAR WITH A FREQUENCY OF 1,000 MEGAHERTZ AND A 0° ELEVATION ANGLE

the attenuation coefficient introduces an error that can be significant for high frequency radar at low elevation angles.

The following technique was devised to reduce the errors. Users of this program will need to use this technique for the particular frequency and elevation angle of the radar they plan to examine. For a 2-D radar, only one calculation may need to be made at the elevation angle of the radar's main beam. For 3-D radars, calculations should be made for each beam grouping. Again, for 3-D radars, the program should be run as separate cases corresponding to the target's flight profile through the appropriate beam grouping while using the attenuation for that beam grouping.

Table 2 presents the one-way attenuation losses for a 1000 megahertz radar and 0^{o} elevation angle.

TABLE 2

ATTENUATION LOSS

Range (n.mi.)	20	40	60	80	100	120	140	160	180	200	220	240	260	280	300
Loss (db)	.21	.40	.59	.77	.93	1.08	1.20	1.29	1.35	1.40	1.45	1.48	1.49	1.50	1.50

The values were determined by taking the appropriate values from figure 4 (two-way attenuation) and dividing them by two. A natural logarithmic curve-fitting technique is used to determine an attenuation coefficient. The following regression equation is used:

$$\alpha = \alpha_1 + \alpha_2 \text{ Ln } R \qquad (25)$$

To simplify the work, the regression coefficients, α_1 and α_2, are changed to attenuation losses from the atmospheric attenuation curve (figure 4) by first multiplying equation 25 by range:

$$R\alpha = R\alpha_1 + R\alpha_2 \text{ Ln } R \qquad (26a)$$

$$L = L_1 + L_2 \text{ Ln } R \qquad (26b)$$

where L is the attenuation loss corresponding to range R (these values are identified in table 2). A regression is accomplished and L_1 and L_2 are inserted into the radar detection model as inputs X(7) and X(8). The radar detection model will take the inputs, calculate the attenuation loss at the target range being examined, convert the attenuation loss to an attenuation coefficient in decibels per nautical mile, and convert it to an attenuation coefficient per nautical mile.

As an example, a natural logarithmic regression on the data in table 2 was accomplished with the loss coefficients determined to be:

$$L = L_1 + L_2 \text{ Ln } R \qquad \text{(see equation 26b)}$$

$$L = -1.55605 + 0.54851 \text{ Ln } R \quad .$$

A correlation coefficient of 0.98 was determined for the regression. Using the t-test, the correlation coefficient tested significant at the 99 percent confidence level.

The results of using the natural logarithmic regression method are displayed in figure 7. The theoretical loss curve was taken from figure 4.

In a later section, a fictitious radar will be modeled for example purposes. The regression coefficients determined above will be used as inputs to the detection model.

MULTIPATH

The effect of multipath interference occurs when the radar signal reflects off the surface such that some of the radiation reaches the target by a reflected path (R_1 and R_2, see figure 5) in addition to the direct path (RT). These two rays generally arrive at the target with both a phase and amplitude difference. The field strength is the phasor sum of these two rays.

The geometry of the multipath problem is shown in figure 8, where:

RT = target range

H_1 = radar antenna height

H_2 = target altitude

RE = effective radius of the earth that includes refraction

$\Psi_1 = \Psi_2$ = angle of incidence = angle of reflection

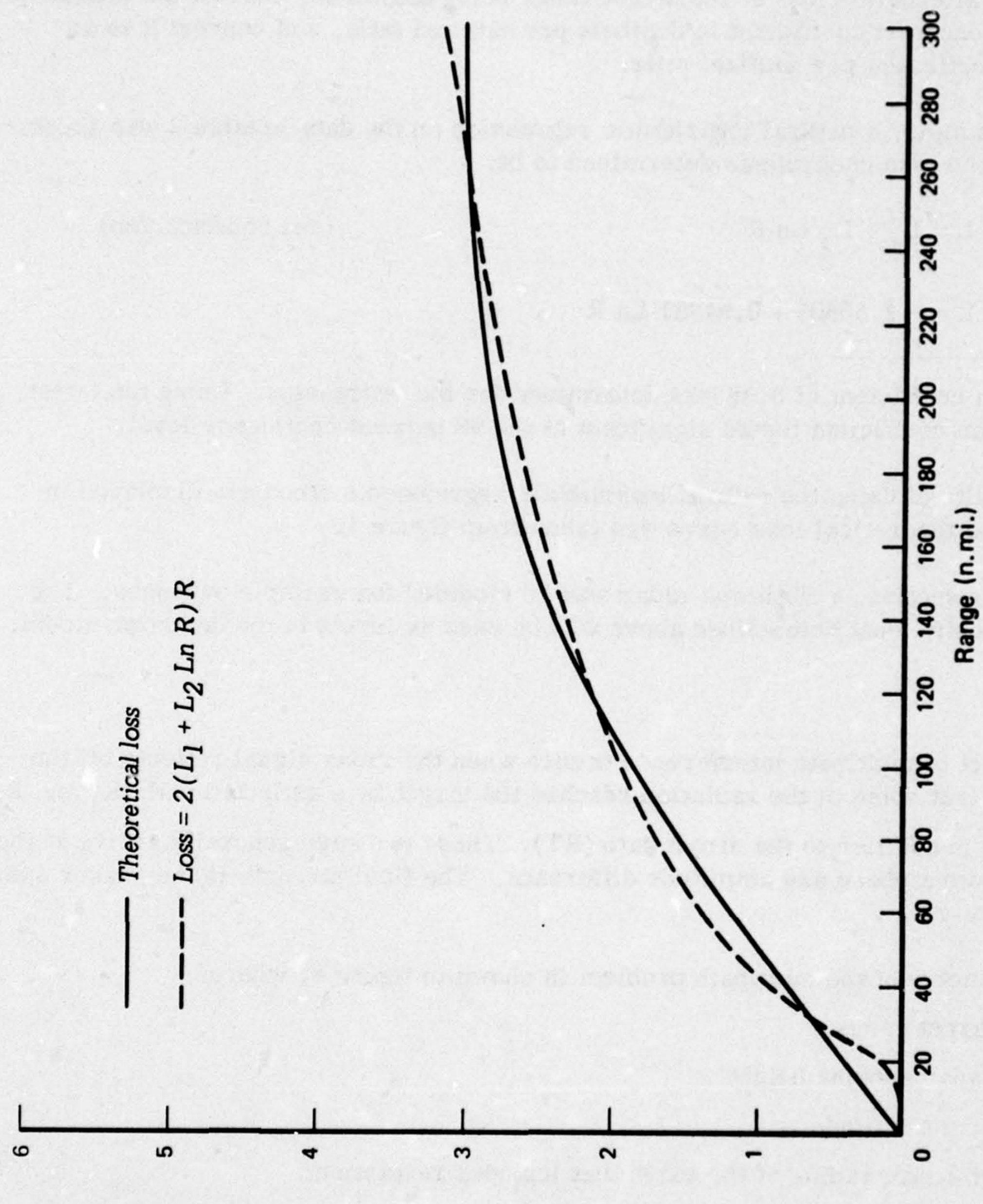

FIG. 7: ATTENUATION COMPARISON

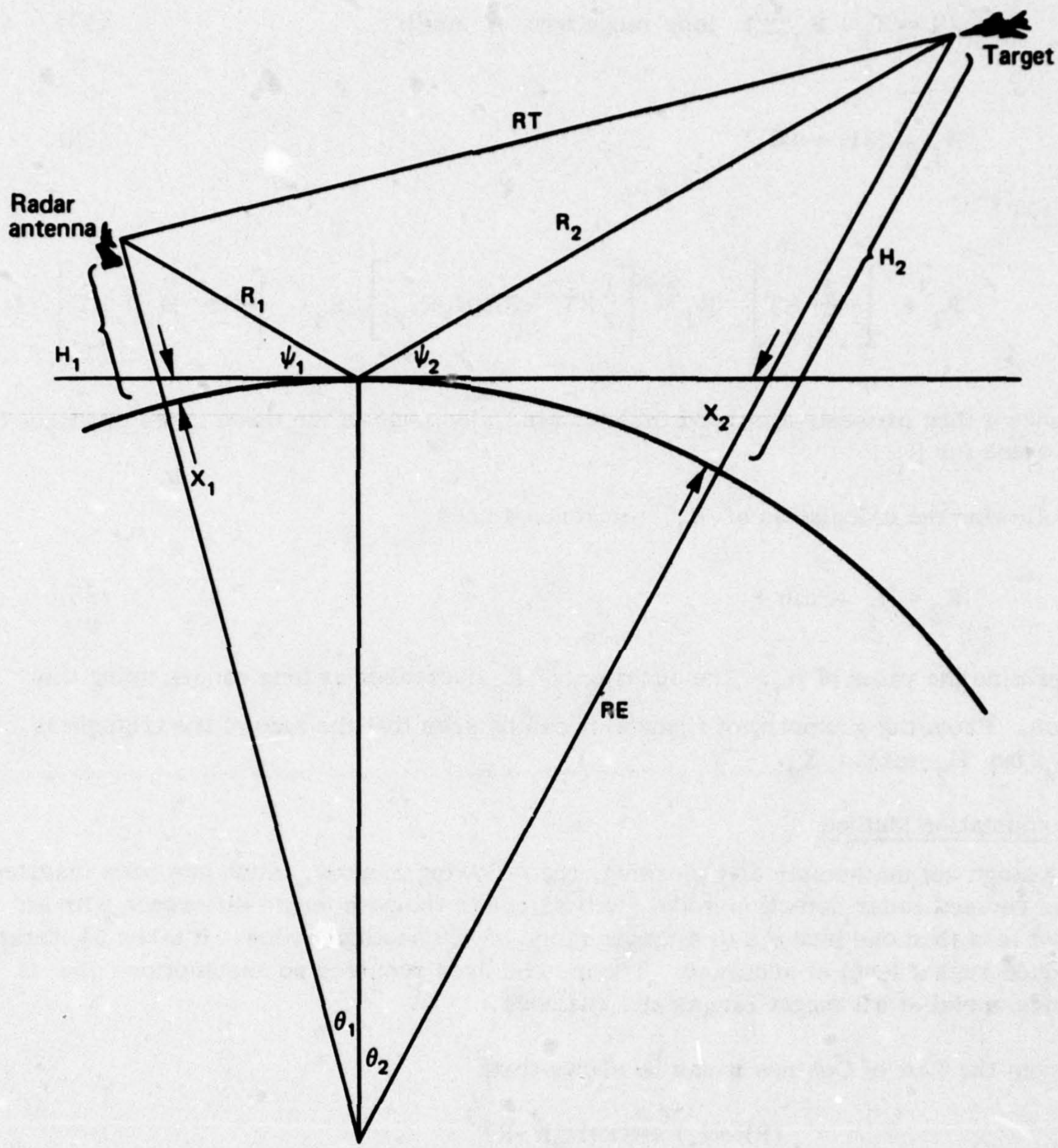

FIG. 8: GEOMETRY OF RADAR MULTIPATH PROBLEM

Reference 4, using the assumptions:

$$RT \approx R_1 + R_2 \Longrightarrow \text{long range with } \Psi \text{ small} \tag{27}$$

and

$$H_1 \div 2RE \longrightarrow 0 \tag{28}$$

shows that:

$$R_1^{\,3} + \left[-\frac{3}{2}RT\right] R_1^{\,2} + \left[\frac{1}{2}RT^2 - RE(H_1+H_2)\right] R_1 + \left[RE \cdot H_1 \cdot RT\right] = 0 \tag{29}$$

Reference 4 then presents a method to determine which one of the three roots produces the actual value for R_1.

Following the calculation of R_1, reference 4 uses:

$$R_2 = H_2 \div \sin \Psi \tag{30}$$

to determine the value of R_2. The accuracy of R_2 decreases at long ranges using this equation. From the geometry of figure 8 it can be seen that the side of the triangle is not H_2 but H_2 minus X_2.

Computation Method

Although not mathematically pleasing, the following method, which has been inserted into the revised radar detection model, will calculate the path length difference with an error of less than one inch out to a target range of 300 nautical miles. It takes 31 iterations to produce such a level of accuracy. The method used requires no assumptions and is therefore useful at all target ranges and altitudes.

From the Law of Cosines it can be shown that:

$$\cos(\theta_1+\theta_2) = \frac{(RE+H_1)^2+(RE+H_2)^2-RT^2}{2(RE+H_1)(RE+H_2)} \tag{31}$$

$$\theta_1+\theta_2 = \arccos\left[\cos(\theta_1+\theta_2)\right] \tag{32}$$

Although the sum of θ_1 plus θ_2 can be found, the individual values are not known. Define an interval 0 degrees to $(\theta_1+\theta_2)$ degrees. In the first iteration, let $\theta_1=1/2\,(\theta_1+\theta_2)$. Using this assumption, R_1 can be computed from the Law of Cosines:

$$\cos\theta_1 = \frac{RE^2 + (RE+H_1)^2 - R_1^{\,2}}{2 \cdot RE \cdot (RE+H_1)} \tag{33}$$

Equation 33 can be solved for R_1:

$$R_1 = \sqrt{RE^2 + (RE+H_1)^2 - 2(RE)(RE+H_1)\cos\theta_1} \tag{34}$$

Using the R_1 determined by the assumed θ_1, Ψ_1 can be computed using the Law of Cosines:

$$\cos\left(\frac{\pi}{2} + \Psi_1\right) = \frac{RE^2 + R_1^{\,2} - (RE+H_1)^2}{2(RE)(R_1)} \tag{35}$$

$$-\sin\Psi_1 = \cos\left(\frac{\pi}{2} + \Psi_1\right) \qquad \text{(trigonometric identity)}$$

$$\sin\Psi_1 = \frac{(RE+H_1)^2 - (RE^2) - (R_1^{\,2})}{2(RE)(R_1)}$$

$$\Psi_1 = \arcsin(\sin\Psi_1) \tag{36}$$

Similarly,

$$R_2 = \sqrt{RE^2 + (RE+H_2)^2 - 2(RE)(RE+H_2)\cos\theta_2} \tag{37}$$

$$\Psi_2 = \arcsin\left[\frac{(RE+H_2)^2 - RE^2 - R_2^{\,2}}{2(RE)(R_2)}\right] \tag{38}$$

Now test Ψ_1 against Ψ_2. If $\Psi_1>\Psi_2$, redefine the interval as θ_1 degrees to $(\theta_1+\theta_2)$ degrees. If $\Psi_1<\Psi_2$, redefine the interval as 0 degrees to θ_1 degrees. Recalculate Ψ_1 and Ψ_2 with θ_1 assumed to be one-half of the new interval.

This method will reduce the error between the initially assumed θ_1 and the actual θ_1 by a factor of $1/2^N$ (where N is the number of iterations). In 31 iterations, this method will reduce the error between Ψ_1 and Ψ_2 such that the error between the calculated point of reflection and the actual point of reflection is less than one inch.

The program in appendix E was taken from the revised detection model to test the accuracy of the method. Tables E-1 through E-4 are results at various target ranges and altitudes.

An error of less than one inch in the point of reflection would create a negligible error in the phase shift caused by the path length difference.

REFERENCES

1. Skolnik, M.I., "Introduction to Radar Systems," McGraw-Hill, New York 1962
2. Naval Weapons Center, China Lake, NWC Technical Memorandum 2698, "Radar System Performance Modeling with Environmental Effects (Preliminary Report)," Unclassified, Feb 1976
3. Not used.
4. Applied Physics Laboratory, Johns Hopkins University, MRD-0-184, "A Program for Computing Radar Multipath Effects," Unclassified, 27 Mar 1968
5. Skolnik, M.I., "Radar Handbook," McGraw-Hill, New York 1970
6. Center for Naval Analyses, Memorandum (CNA)77-0448, "Data 2 (24-66)," Unclassified, 6 Apr 1977
7. Center for Naval Analyses, Memorandum (CNA)77-0449, "Revised Plotter Package, (CNA Program 10-68S (J7 CNA PLOTTER 2))," Unclassified, 6 Apr 1977

APPENDIX A

USERS' GUIDE

APPENDIX A

USERS' GUIDE

USERS' GUIDE

General

This appendix provides users' instructions for the radar detection model. The control cards, the DATA2 subroutine, and the PLOTTER2 subroutine are specifically for CNA's computer (CDC 3800). It is recommended that non-CNA users replace the DATA2 and PLOTTER2 subroutines with similar routines within your own system. The radar detection model is written in FORTRAN, which may be useable on other computers with minimal modifications.

Control Cards

A typical card deck is shown in figure A-1 . The DATA2 subroutine for reading in data allows for several cases to be run at one time.

DATA2 Subroutine

The DATA2 subroutine is used to read in 34 input parameters and locate them in an array. The subroutine has two beneficial features. It allows free field, formatless use of input cards, and the contents of the array are zeroed only at the beginning of a job, not between cases.

In using the free field feature, the first number on the input card identifies an element in the input array. The next number is the value that will be placed into that element specified by the first number. The third number is the value that will be placed in the next sequential element of the array. Additional numbers will be placed in subsequent, sequential elements. There must be at least one space between each number (e.g., 78 135 1E6...). Input cards are read in sequence for a given case until a blank card is reached.

The array is zeroed at the beginning of a job. All values used in the first case of a job are continued into the second case, except those specifically changed. The same process occurs for subsequent cases. This feature allows changing parameters between cases without having to reenter the entire input deck. Only those parameters to be changed need be specified after the first case. Documentation and a more thorough discussion of DATA2 are found in reference A-6.

The following example may assist the user in understanding the use of DATA2. Figure A-2 presents input decks. Sample case 1 has six values (table A-1) to be entered.

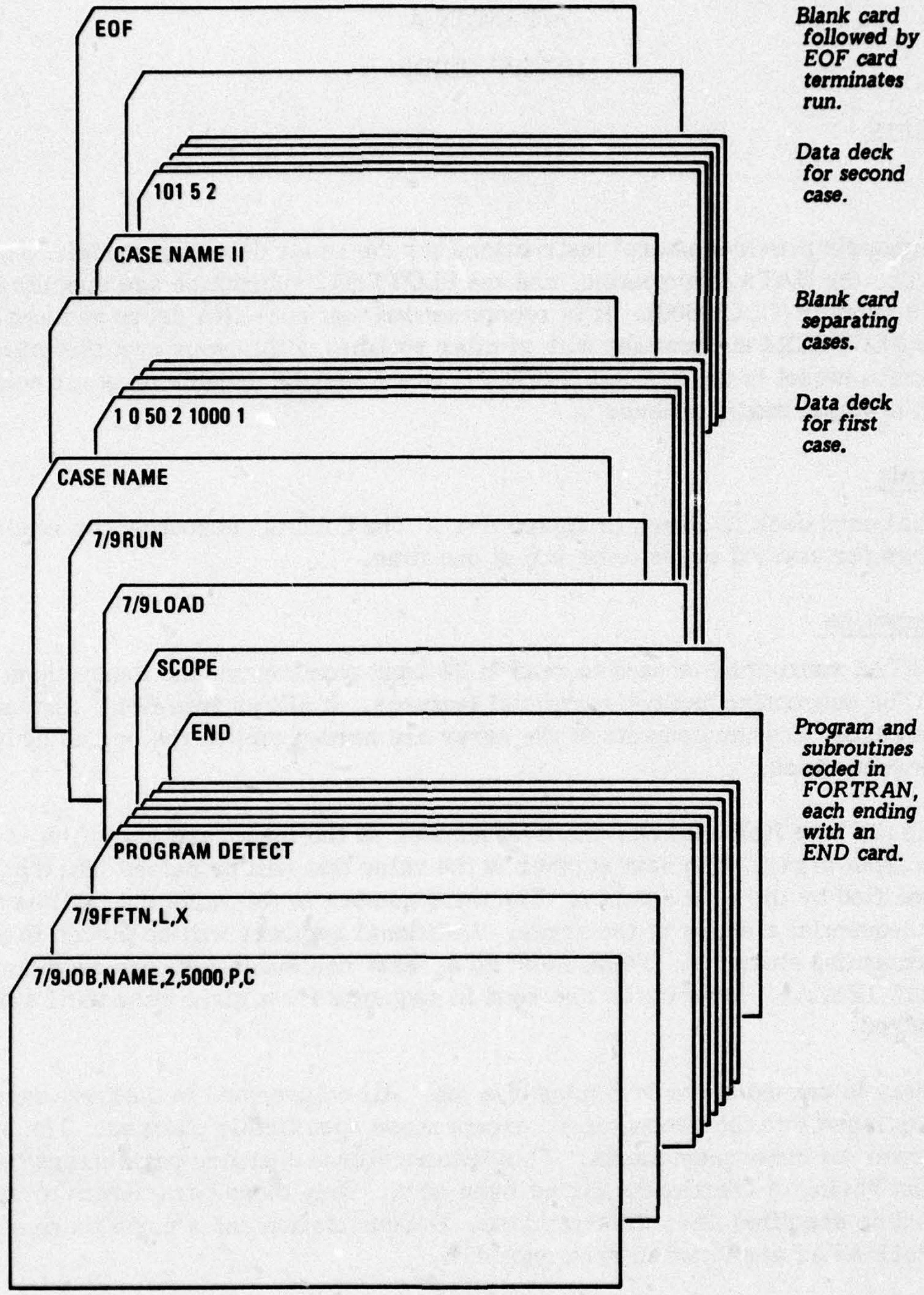

FIG. A-1: TYPICAL CARD DECK

TABLE A-1

INPUT VALUES

Element in the array	Value
1	16
2	80
3	.5
4	16, 000
5	-12
6	.001

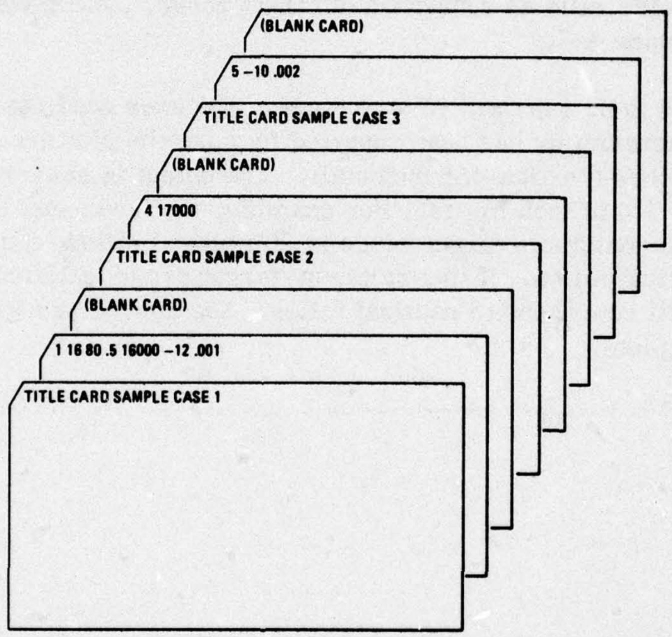

FIG. A-2: DATA2 EXAMPLE

In sample case 2, we wish to change input 4 from 16, 000 to 17, 000. Note that the other values need not be included. In sample case 3, we wish to change input 5 from -12 to -10 and input 6 from .001 to .002 . Again, inputs that have not been changed remain the same as in the previous case. Table A-2 identifies the input values to be used in sample case 3.

TABLE A-2

INPUT VALUES

Element in the Array	Value
1	16
2	80
3	.5
4	17,000
5	-10
6	.002

PLOTTER2 Subroutine

The PLOTTER2 subroutine takes the output from the radar detection model and plots the signal-to-noise ratio as a function of target range. Documentation of PLOTTER2 is contained in reference A-7.

If the program is to be run on CNA's computer, the user need not be concerned with this subroutine. Programming has been inserted to make the plotting automatic. The plot will be 7 x 10 inches (vertical x horizontal). The output is scaled for maximum projection within the 7 x 10 inch limits. For example, the horizontal axis has 10 scaling marks. If the maximum target range is 50 nautical miles, the scaling marks will represent 5 nautical miles. If the maximum target range is 150 nautical miles, the scaling marks will represent 15 nautical miles. See appendixes B and C for examples of the output plots.

APPENDIX B

STANDOFF JAMMING EXAMPLE

APPENDIX B

STANDOFF JAMMING EXAMPLE

In order to assist a future user to understand the radar detection model, two examples will be provided. It is emphasized that the radar and the threats in the scenario are fictitious. The two examples will use the same radar, threat missile, and environmental conditions. In this appendix, we shall examine standoff noise jamming. The following appendix will assume a missile with a self-screening noise jammer but no standoff jamming.

The basic scenario is as follows. The ship is in sea state two (Beaufort scale) and multipath interference can be expected. The atmospheric attenuation can be described by the regression coefficients calculated in the previous section on attenuation.

$$L = L_1 + L_2 \text{ Ln } R$$

$$L - 1.55605 + 0.54851 \text{ Ln } R$$

A surface clutter coefficient of -30 decibels was determined from reference 1 (pages 527-534). There is a drizzle with a rainfall rate of 1 millimeter per hour. A coefficient of refractivity of 1.333 is assumed, corresponding to the 4/3 earth approximation.

The user has researched various reference publications. Table B-1 lists the characteristics of the radar determined from the references.

The fictitious threat missile has a one square meter radar cross section. The missile is launched from 150 nautical miles at an altitude of 15, 000 feet. The missile has an unspecified homing device that is locked onto the ship prior to launch. The missile flies a constant azimuth, constantly decreasing altitude flight profile from launch at 15, 000 feet until it hits the ship.

There are four enemy jamming aircraft at 150 nautical miles. Each jamming aircraft is separated by 90 degrees. Each aircraft has a jamming capability of 1, 000 watts over a bandwidth of 10 megahertz. The threat missile may be launched from any one of the four aircraft. As a result, the threat missile will always be in a main-lobe jamming strobe of one of the four aircraft. The other three aircraft will be jamming into the radar's side-lobes.

The inputs to the detection model are presented in table B-2. Figure B-1 provides the input deck. The numerical outputs (table B-3) and the graphical outputs (figure B-2) present the results of the first example.

TABLE B-1

FICTITIOUS RADAR PARAMETERS

Parameter	Value
Peak transmitted power (kw)	1000
Antenna gain, main-lobe (db)	35
Antenna gain, side-lobe (db down from main-lobe, db)	25
Operating frequency (Mhz)	1000
Receiver noise bandwidth (Mhz)	10
Receiver noise figure (db)	5
Integration improvement in S/N ratio (db)	50
System losses (db)	1
Pulse length (usec)	.5
Azimuth beamwidth (down 3 db level, deg)	5
Antenna height (ft)	100
Polarization	Horizontal

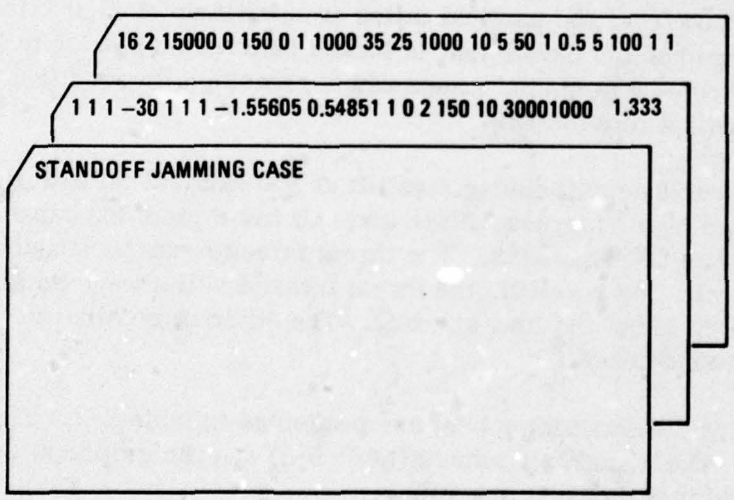

FIG. B-1: STANDOFF JAMMING EXAMPLE INPUT DECK

TABLE B-2

RADAR DETECTION MODEL INPUTS

INPUT	DEFINITION	VALUE
X(1)	multipath effect included (1=yes; 0=no)	1
X(2)	surface clutter included (1=yes; 0=no)	1
X(3)	surface clutter coefficient in decibels. A ratio of 1 square meter of clutter to 1,000 square meters illuminated would be entered as -30 (see reference 1, pages 527-534)	-30
X(4)	weather clutter included (1=yes; 0=no)	1
X(5)	rainfall rate in millimeters per hour	1
X(6)	attenuation included (1=yes; 0=no)	1
X(7) and X(8)	$X(7)=L_1$ and $X(8)=L_2$ of natural logarithmic regression $L=L_1+L_2LnR$, where L is the attenuation loss in decibels and R is target range in nautical miles (see section on attenuation	-1.55605 0.54851
X(9)	jamming included (1=yes; 0=no)	1
X(10)	type of jammer (0=standoff jammer; 1=self-screening jammer)	0
X(11)	location of jammming (0=side-lobe; 1=main-lobe; 2=both main- and side-lobes)	2
X(12)	range from radar to jammers in nautical miles. Note: all jammers must be at the same range	150
X(13)	noise jammer bandwidth in megahertz. Note: all jammers must have identical bandwidths	10
X(14)	effective radiated power of the jammer(s) in watts. Packed word "SSSSMMMM" where "SSSS" refers to side-lobe jamming and "MMMM" refers to main-lobe jamming. Note: all jamming power in the appropriate lobe must be totaled and entered as one value. For example, three 100 watt jammers in the side-lobe and two 100 watt jammers in the main-lobe would be entered as 03000200.	03000100

TABLE B-2 (Cont'd)

INPUT	DEFINITION	VALUE
X(15)	coefficient of refractivity (1.333 for the 4/3 earth approximation)	1.333
X(16)	sea state (Beaufort scale)	2
X(17)	target altitude at the beginning of the run (in feet)	15,000
X(18)	target altitude at the end of the run (in feet)	0
X(19)	target range at the beginning of the run (in nautical miles)	150
X(20)	target range at the end of the run (in nautical miles)	0
X(21)	average target cross section (in square meters)	1
X(22)	Peak radar transmitted power (in kilowatts)	1000
X(23)	main-lobe antenna gain (in decibels)	35
X(24)	side-lobe antenna gain (in decibels)(e.g., side-lobe down 25 db from the main-lobe gain would be entered as 25)	25
X(25)	radar frequency (in megahertz)	1000
X(26)	receiver noise bandwidth (in megahertz)	10
X(27)	receiver noise figure (in decibels)	5
X(28)	integration improvement in S/N ratio (in decibels)(e.g., if the radar integrates 100 pulses, perfect integration improvement would be entered as 20)(see reference 1, pages 35-40)	50
X(29)	radar system losses (in decibels)	1
X(30)	radar pulse length (in microseconds)	.5
X(31)	azimuth beamwidth in degrees measured at the 3 db down level	5
X(32)	radar antenna height (in feet)	100
X(33)	radar polarization (0=vertical; 1=horizontal)	1
X(34)	output in graph form (1=yes; 0=no)	1

TABLE B-3

STANDOFF JAMMING EXAMPLE

0.0	95.2	50.0	32.8	100.0	8.3
1.0	-127.6	51.0	31.9	101.0	9.4
2.0	2.7	52.0	22.0	102.0	6.5
3.0	36.3	53.0	27.1	103.0	4.6
4.0	49.2	54.0	22.9	104.0	1.8
5.0	54.8	55.0	19.1	105.0	-11.0
6.0	57.8	56.0	22.6	106.0	-7.3
7.0	59.1	57.0	17.3	107.0	-5.0
8.0	59.6	58.0	5.7	108.0	-19.0
9.0	18.2	59.0	15.7	109.0	-19.1
10.0	55.1	60.0	-10.7	110.0	-11.4
11.0	44.3	61.0	-28.7	111.0	-22.4
12.0	40.5	62.0	-6.0	112.0	-14.3
13.0	24.1	63.0	-4.5	113.0	-1.1
14.0	7.5	64.0	-38.2	114.0	-1.1
15.0	31.9	65.0	4.5	115.0	-0.0
16.0	40.2	66.0	9.8	116.0	1.5
17.0	4.6	67.0	10.6	117.0	7.5
18.0	21.6	68.0	10.6	118.0	7.6
19.0	27.3	69.0	18.2	119.0	8.8
20.0	-27.2	70.0	13.7	120.0	11.7
21.0	26.7	71.0	16.1	121.0	12.1
22.0	-5.5	72.0	21.8	122.0	12.5
23.0	27.4	73.0	21.5	123.0	14.1
24.0	-32.1	74.0	22.1	124.0	13.8
25.0	26.5	75.0	24.2	125.0	14.4
26.0	12.0	76.0	21.3	126.0	14.5
27.0	-31.7	77.0	23.9	127.0	15.1
28.0	26.9	78.0	24.3	128.0	15.4
29.0	11.6	79.0	24.7	129.0	15.4
30.0	14.0	80.0	25.0	130.0	15.4
31.0	17.6	81.0	25.8	131.0	15.2
32.0	8.6	82.0	25.5	132.0	15.4
33.0	21.3	83.0	25.7	133.0	15.1
34.0	42.4	84.0	25.6	134.0	15.0
35.0	41.0	85.0	25.3	135.0	14.6
36.0	41.6	86.0	25.1	136.0	14.3
37.0	41.1	87.0	24.4	137.0	14.0
38.0	40.6	88.0	24.0	138.0	13.3
39.0	40.2	89.0	23.3	139.0	13.2
40.0	39.3	90.0	23.7	140.0	12.5
41.0	39.2	91.0	23.4	141.0	12.2
42.0	37.9	92.0	22.2	142.0	11.7
43.0	36.4	93.0	21.2	143.0	10.7
44.0	37.1	94.0	20.0	144.0	10.0
45.0	33.4	95.0	18.5	145.0	8.5
46.0	34.2	96.0	17.3	146.0	8.6
47.0	34.4	97.0	15.8	147.0	7.0
48.0	32.4	98.0	13.8	148.0	5.9
49.0	32.4	99.0	15.6	149.0	5.7

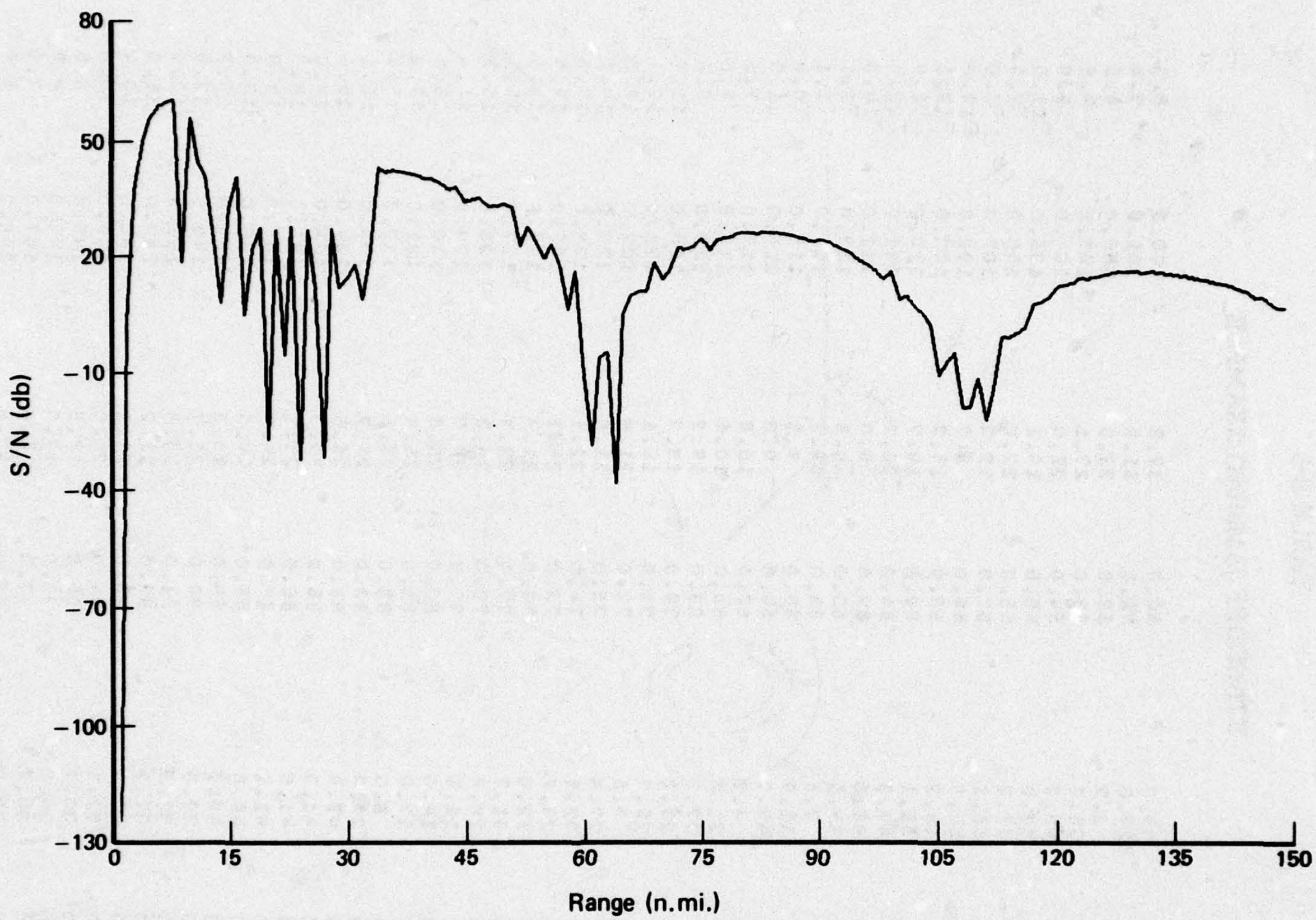

FIG. B-2: STANDOFF JAMMING EXAMPLE

APPENDIX C

SELF-SCREENING JAMMING EXAMPLE

APPENDIX C

SELF-SCREENING JAMMING EXAMPLE

SELF-SCREENING JAMMING EXAMPLE

In this example, the characteristics of the radar, threat missile, and environment are identical to the scenario in appendix B. There is only one enemy aircraft that launches the threat missile. There are no standoff jamming aircraft. The threat missile has a self-screening noise jammer on board with 10 watts of power over a 10 megahertz bandwidth. The threat missile flies the same flight profile as in appendix B.

The inputs to the detection model are presented in table C-1. Figure C-1 provides the input deck. The numerical outputs (table C-2) and the graphical outputs (figure C-2) present the results of the self-screening jamming example.

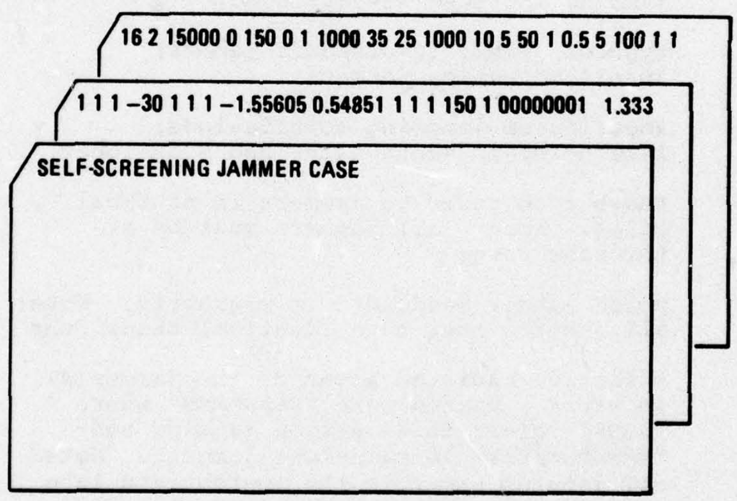

FIG. C-1: SELF-SCREENING JAMMING EXAMPLE INPUT DECK

TABLE C-1

RADAR DETECTION MODEL INPUTS

INPUT	DEFINITION	VALUE
X(1)	multipath effect included (1=yes; 0=no)	1
X(2)	surface clutter included (1=yes; 0=no)	1
X(3)	surface clutter coefficient in decibels. A ratio of 1 square meter of clutter to 1,000 square meters illuminated would be entered as -30 (see reference 1, pages 527-534)	-30
X(4)	weather clutter included (1=yes; 0=no)	1
X(5)	rainfall rate in millimeters per hour	1
X(6)	attenuation included (1=yes; 0=no)	1
X(7) and X(8)	X(7)=L_1 and X(8)=L_2 of natural logarithmic regression $L=L_1+L_2 LnR$, where L is the attenuation loss in decibels and R is target range in nautical miles (see section on attenuation	-1.55605 0.54851
X(9)	jamming included (1=yes; 0=no)	1
X(10)	type of jammer (0=standoff jammer; 1=self-screening jammer)	1
X(11)	location of jammming (0=side-lobe; 1=main-lobe; 2=both main- and side-lobes)	1
X(12)	range from radar to jammers in nautical miles. Note: all jammers must be at the same range	150
X(13)	noise jammer bandwidth in megahertz. Note: all jammers must have identical bandwidths	10
X(14)	effective radiated power of the jammer(s) in watts. Packed word "SSSSMMMM" where "SSSS" refers to side-lobe jamming and "MMMM" refers to main-lobe jamming. Note: all jamming power in the appropriate lobe must be totaled and entered as one value. For example, three 100 watt jammers in the side-lobe and two 100 watt jammers in the main-lobe would be entered as 03000200	00000010

TABLE C-1 (Cont'd)

INPUT	DEFINITION	VALUE
X(15)	coefficient of refractivity (1.333 for the 4/3 earth approximation)	1.333
X(16)	sea state (Beaufort scale)	2
X(17)	target altitude at the beginning of the run (in feet)	15,000
X(18)	target altitude at the end of the run (in feet)	0
X(19)	target range at the beginning of the run (in nautical miles)	150
X(20)	target range at the end of the run (in nautical miles)	0
X(21)	average target cross section (in square meters)	1
X(22)	Peak radar transmitted power (in kilowatts)	1000
X(23)	main-lobe antenna gain (in decibels)	35
X(24)	side-lobe antenna gain (in decibels)(e.g., side-lobe down 25 db from the main-lobe gain would be entered as 25)	25
X(25)	radar frequency (in megahertz)	1000
X(26)	receiver noise bandwidth (in megahertz)	10
X(27)	receiver noise figure (in decibels)	5
X(28)	integration improvement in S/N ratio (in decibels)(e.g., if the radar integrates 100 pulses, perfect integration improvement would be entered as 20)(see reference 1, pages 35-40)	50
X(29)	radar system losses (in decibels)	1
X(30)	radar pulse length (in microseconds)	.5
X(31)	azimuth beamwidth in degrees measured at the 3 db down level	5
X(32)	radar antenna height (in feet)	100
X(33)	radar polarization (0=vertical; 1=horizontal)	1
X(34)	output in graph form (1=yes; 0=no)	1

TABLE C-2

SELF-SCREENING JAMMING EXAMPLE

0.0	61.8	50.0	32.1	100.0	14.3
1.0	71.1	51.0	31.4	101.0	15.6
2.0	62.4	52.0	21.7	102.0	12.9
3.0	59.1	53.0	26.9	103.0	11.0
4.0	56.8	54.0	23.0	104.0	3.4
5.0	54.9	55.0	19.3	105.0	¯4.5
6.0	53.7	56.0	23.0	106.0	¯0.7
7.0	52.5	57.0	17.9	107.0	1.7
8.0	51.5	58.0	6.5	108.0	¯12.2
9.0	9.3	59.0	16.6	109.0	¯12.2
10.0	45.7	60.0	¯9.6	110.0	¯4.4
11.0	34.7	61.0	¯27.5	111.0	¯15.3
12.0	30.8	62.0	¯4.6	112.0	¯7.1
13.0	14.4	63.0	¯3.1	113.0	6.1
14.0	¯1.9	64.0	¯36.5	114.0	6.3
15.0	22.6	65.0	6.4	115.0	7.4
16.0	31.1	66.0	11.8	116.0	9.0
17.0	¯4.2	67.0	12.7	117.0	15.1
18.0	13.1	68.0	12.9	118.0	15.3
19.0	18.9	69.0	20.6	119.0	16.5
20.0	¯35.3	70.0	16.2	120.0	19.5
21.0	19.0	71.0	18.8	121.0	20.0
22.0	¯13.0	72.0	24.6	122.0	20.5
23.0	20.2	73.0	24.5	123.0	22.2
24.0	¯39.0	74.0	25.2	124.0	22.0
25.0	19.9	75.0	27.5	125.0	22.7
26.0	5.7	76.0	24.7	126.0	22.8
27.0	¯37.7	77.0	27.4	127.0	23.5
28.0	21.1	78.0	27.9	128.0	23.9
29.0	6.2	79.0	28.4	129.0	23.9
30.0	8.8	80.0	29.6	130.0	24.1
31.0	12.7	81.0	29.8	131.0	23.9
32.0	4.0	82.0	29.6	132.0	24.2
33.0	16.9	83.0	29.9	133.0	24.0
34.0	38.3	84.0	29.9	134.0	23.9
35.0	37.1	85.0	29.7	135.0	23.6
36.0	38.0	86.0	29.6	136.0	23.4
37.0	37.7	87.0	29.1	137.0	23.2
38.0	37.5	88.0	28.7	138.0	22.5
39.0	37.2	89.0	28.1	139.0	22.5
40.0	36.6	90.0	28.7	140.0	21.9
41.0	36.7	91.0	28.5	141.0	21.7
42.0	35.7	92.0	27.4	142.0	21.2
43.0	34.3	93.0	26.5	143.0	20.3
44.0	35.2	94.0	25.5	144.0	19.7
45.0	31.8	95.0	24.0	145.0	18.2
46.0	32.8	96.0	22.9	146.0	18.4
47.0	33.2	97.0	21.5	147.0	16.9
48.0	31.3	98.0	19.7	148.0	15.8
49.0	31.6	99.0	21.6	149.0	15.7

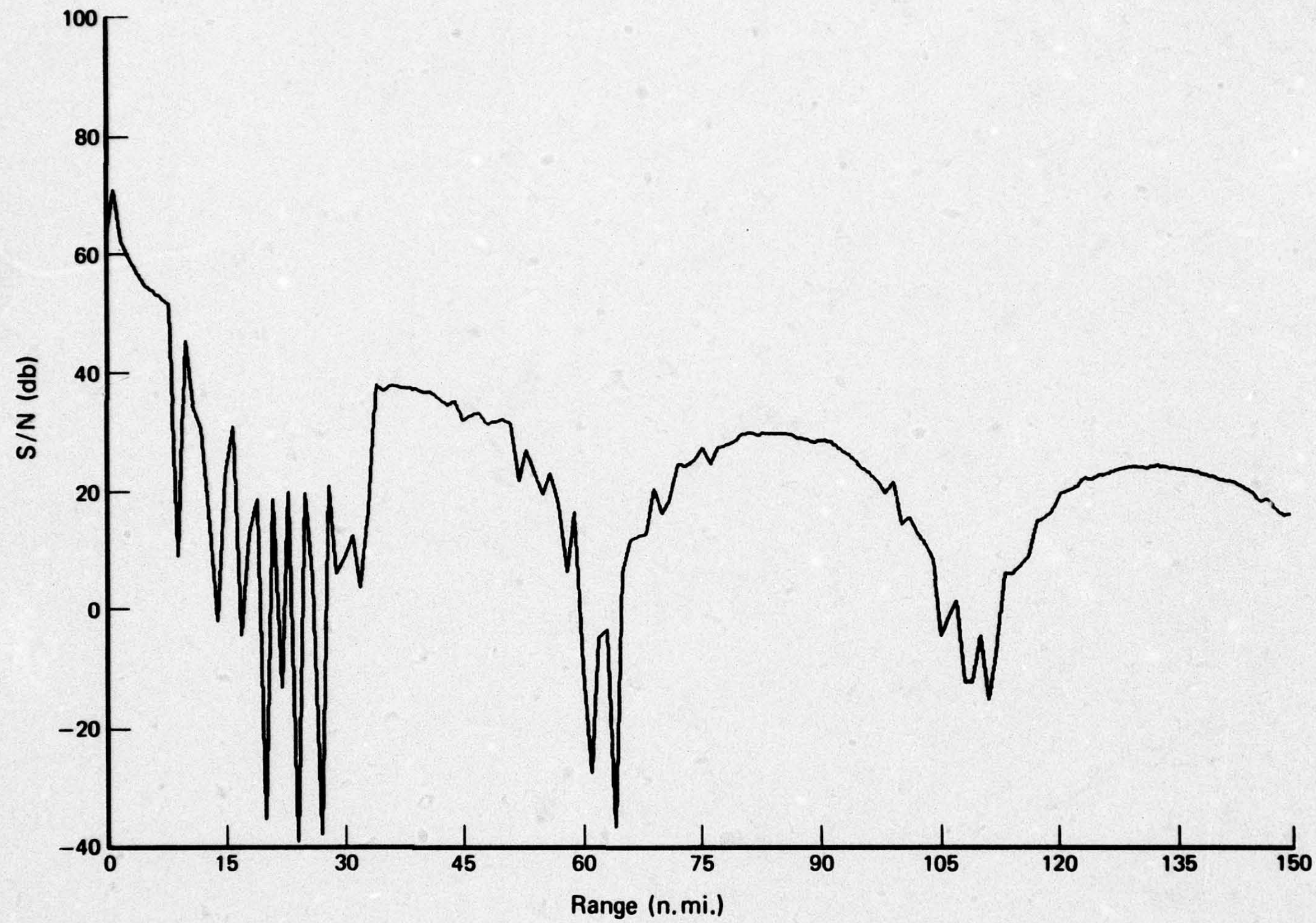

FIG. C-2: SELF-SCREENING JAMMING EXAMPLE

APPENDIX D
RADAR DETECTION MODEL

```
      PROGRAM DETECT
C------------------------------------------------------------------------
C------------------------------------------------------------------------
C     RADAR DETECTION MODEL INVOLVING MULTIPATH EFFECTS,JAMMING,SURFACE
C     CLUTTER, AND WEATHER CLUTTER.  THE JAMMING MAY BE FROM A STAND-OFF
C     JAMMER OR FROM THE TARGET ITSELF(SELF-SCREENING JAMMER).  THE
C     TARGET MAY BE INPUT AT ANY ALTITUDE/RANGE AND HAVE ANY FLIGHT
C     PROFILE ON A RADIAL FROM THE DEFENDING SHIP.
C------------------------------------------------------------------------
C------------------------------------------------------------------------
C------------------------------------------------------------------------
C     RADAR DETECTION MODEL INPUT VARIABLES
C
C     X(1)    MULTIPATH EFFECT INCLUDED(1=YES, 0=NO)
C     X(2)    SURFACE CLUTTER INCLUDED(1=YES, 0=NO)
C     X(3)    SURFACE CLUTTER COEFFICIENT(DB) (EG., A RATIO OF 1 SQUARE
C               METER CLUTTER TO 1000 SQUARE METER ILLUMINATED WOULD BE
C               INPUT AS -30)
C     X(4)    WEATHER CLUTTER INCLUDED(1=YES, 0=NO)
C     X(5)    RAINFALL RATE(MM/HR)
C     X(6)    ATTENUATION INCLUDED(1=YES, 0=NO)
C     X(7)    LOSS(1)     (LOSS = LOSS(1) + LOSS(2) X LN R
C                          SEE RESEARCH CONTRIBUTION FOR CALCULATION OF
C                          LOSS(1) AND LOSS(2) NATURAL LOGARITHMIC
C     X(8)    LOSS(2)      REGRESSION COEFFICIENTS)
C     X(9)    JAMMING INCLUDED(1=YES, 0=NO)
C     X(10)   TYPE OF JAMMER(0=STAND-OFF JAMMER, 1=SELF-SCREENING JAMMER)
C     X(11)   LOCATION OF JAMMING(0=SIDE-LOBE, 1=MAIN-LOBE, 2=BOTH)
C     X(12)   RANGE TO JAMMER(NM)
C     X(13)   NOISE JAMMER BANDWIDTH(MHZ)
C     X(14)   EFFECTIVE RADIATED POWER OF JAMMER(W)
C               (PACKED WORD SSSSMMMM WHERE SSSS REFERS TO SIDE-LOBE
C                JAMMING AND MMMM REFERS TO MAIN-LOBE JAMMING)
C     X(15)   COEFFICIENT OF REFRACTION(1.3333 FOR 4/3 EARTH ASSUMPTION)
C     X(16)   SEA STATE(BEAUFORT SCALE)
C     X(17)   TARGET ALTITUDE AT THE BEGINNING OF THE RUN(FT)
C     X(18)   TARGET ALTITUDE AT THE END OF THE RUN(FT)
C     X(19)   TARGET RANGE AT THE BEGINNING OF THE RUN(NM)
C     X(20)   TARGET RANGE AT THE END OF THE RUN(NM)
C     X(21)   AVERAGE TARGET CROSSSECTION(SQ. M.)
C     X(22)   PEAK TRANSMITTED POWER(KW)
C     X(23)   ANTENNA GAIN, MAIN-LOBE(DB)
C     X(24)   ANTENNA GAIN, SIDE-LOBE(DB) (EG., SIDE-LOBE DOWN 25DB WOULD
C                BE INPUT AS 25)
C     X(25)   OPERATING FREQUENCY(MHZ)
C     X(26)   RECEIVER NOISE BANDWIDTH(MHZ)
C     X(27)   RECEIVER NOISE FIGURE(DB)
C     X(28)   INTEGRATION IMPROVEMENT IN S/N RATIO(DB)
C     X(29)   SYSTEM LOSSES(DB)
C     X(30)   PULSE LENGTH(MICROSECONDS)
C     X(31)   AZIMUTH BEAMWIDTH(DEG)(AT 3DB DOWN LEVEL)
C     X(32)   ANTENNA HEIGHT(FT)
C     X(33)   POLARIZATION(0=VERTICAL, 1=HORIZONTAL)
C     X(34)   PLOTTER OUTPUT(1=YES, 0=NO)
C------------------------------------------------------------------------
```

```
C-----------------------------------------------------------------------
      COMMON X(35),RNM(350),SGNSDB(350),TEMP(10),DELTAR,
     1R1,R2,ANGLE1,ANGLE2,PHI,PHID,PHIV,RRD,RHO,RV,D,ISTOP,PI
C-----------------------------------------------------------------------
C     READ ALPHAMERIC SUBJECT LINE FOR THE OUTPUT PLOT
C-----------------------------------------------------------------------
    1 READ 10, (TEMP(I),I=1,10)
   10 FORMAT (10A8)
      IF (EOF,60) 100,20
   20 PRINT 1000,(TEMP(I),I=1,10)
 1000 FORMAT (1H1,10A8)
C-----------------------------------------------------------------------
C     READ PARAMETERS INTO THE PROGRAM
C-----------------------------------------------------------------------
      CALL DATA2(X,60,IND)
      IF (IND.GT.0) GO TO 100
      PRINT 30, ((I,X(I)),I=1,35)
   30 FORMAT (5X,7(I4*=*F10.4),I4*=*,F10.7/5X,5(I4*=*F10.4),I4*=*F10,
     -2(I4*=*F10.4)/2(5X,8(I4*=*F10.4)/),5X,2(I4*=*F10.4),I4*=*F15.12/)
C-----------------------------------------------------------------------
C     COMPUTE SIGNAL-TO-NOISE RATIO AS A FUNCTION OF RANGE
C-----------------------------------------------------------------------
      CALL RADRNG(ISTART)
      IF (X(34).EQ.0.) GO TO 1999
C-----------------------------------------------------------------------
C     DETERMINE SCALING FACTORS FOR THE OUTPUT PLOT
C-----------------------------------------------------------------------
      SNMAX = SNMIN = SGNSDB(ISTOP)
      IBEGIN = ISTART+1
      IEND = ISTOP
      DO 50  JJ=IBEGIN,IEND
      IF (SGNSDB(JJ).LT.SGNSDB(JJ-1)) GO TO 40
      IF (SGNSDB(JJ).GT. SNMAX)  SNMAX=SGNSDB(JJ)
      GO TO 50
   40 IF (SGNSDB(JJ).GT.SGNSDB(JJ-1)) GO TO 50
      IF (SGNSDB(JJ).LT. SNMIN)  SNMIN=SGNSDB(JJ)
   50 CONTINUE
      SNMIN =((INTF( SNMIN/10.))*10)-10.
   60 SGNSDB(ISTOP +1)= SNMIN
      SNMAX =((INTF((( SNMAX- SNMIN)/7)/10))*10)+10.
      SGNSDB(ISTOP +2)= SNMAX
      RNM(ISTOP +1)=0.
      IF (ISTOP .LE.50)  RNM(ISTOP +2)=5.
      IF (ISTOP .LE.50)  GO TO 70
      IF (ISTOP .LE.100)  RNM(ISTOP +2)=10.
      IF (ISTOP .LE.100)  GO TO 70
      IF (ISTOP .LE.150)  RNM(ISTOP +2)=15.
      IF (ISTOP .LE.150)  GO TO 70
      IF (ISTOP .LE.200)  RNM(ISTOP +2)=20.
      IF (ISTOP .LE.200)  GO TO 70
      IF (ISTOP .LE.250)  RNM(ISTOP +2)=25.
      IF (ISTOP .LE.250)  GO TO 70
      IF (ISTOP .LE.300)  RNM(ISTOP +2)=30.
   70 IPRINT = IEND+2
      NUMBER=(ISTOP-ISTART)+1
```

```
      INUM = 1
      DO 9999 JI = ISTAPT,IPPINT
      RNM(INUM) = RNM(JI)
      SGNSDB(INUM) = SGNSDB(JI)
      INUM = INUM+1
 9999 CONTINUE
C-------------------------------------------------------------------------
C     PLOT SIGNAL-TO-NOISE RATIO AS A FUNCTION OF RANGE
C-------------------------------------------------------------------------
      CALL PLOTTER2 (RNM,SGNSDB,NUMBER,80,14HRANGE (N. MI.),14,
     18HS/N (DB),8,TEMP,80,6)
 1999 CONTINUE
      PRINT 2000
 2000 FORMAT (11X,*RNG*,7X,*S/N*)
      DO 5000 I = 1,NUMBER
      PRINT 3000,I,RNM(I),SGNSDB(I)
 3000 FORMAT (I4,F10.1,F10.1)
 5000 CONTINUE
      GO TO 1
  100 END
```

```
      SUBROUTINE RADRNG(ISTART)
C-----------------------------------------------------------------------
C     SUBROUTINE TO DETERMINE SIGNAL-TO-NOISE RATIO AS A FUNCTION OF RANGE
C-----------------------------------------------------------------------
      COMMON X(35),FNM(350),SGNSDB(350),TEMP(10),DELTAR,
     1R1,R2,ANGLE1,ANGLE2,PHI,PHID,PHIV,RRD,RHO,RV,D,ISTOP,PI
      DIMENSION ALPHA1(2)
      DB(ZZ)=10*ALOG10(ZZ)
      UNDB(ZZZ)=10.**(ZZZ/10)
C-----------------------------------------------------------------------
C     CONVERT INPUT VARIABLE TO UNITS OF MEASURE NECESSARY FOR COMPUTATION
C-----------------------------------------------------------------------
      XMPATH=X(1)
      SURFCE=X(2)
      SIGO=UNDB(X(3))
      WEATHR=X(4)
      RAIN=X(5)
      ATTNTN=X(6)
      ALPHA1(1) = X(7)
      ALPHA1(2) = X(8)
      XJAM=X(9)
      TYPJAM=X(10)
      STBJAM=X(11)
      RJ=X(12)*1852.0035
      BJ=X(13)*(10.**6)
      PJGJ=X(14)
      RE=20891199*X(15)
      WAVETH=10.*((X(16)/10.)**2)
      ALTBGN = X(17)
      ALTEND=X(18)
      RNGBGN = X(19)*6076.11549
      RNGEND = X(20)*6076.11549
      SIGT=X(21)
      PT=X(22)*1000.
      GT=UNDB(X(23))
      GT1=UNDB(X(24))
   10 GT1=GT/GT1
   20 WAVELT=299.7925/X(25)
      BN=X(26)*(10.**6)
      FN=UNDB(X(27))
      XNEIN=UNDB(X(28))
      SL=UNDB(X(29))
      TAU=X(30)/(10.**6)
      BZ=X(31)*.017453293
      H1=X(32)
      RPOLAR=X(33)
      SIGJAM=0.
      DBDP=0.
      CLT=2.937925*(10.**8)
      C=1.38/(10.**23)
      TO=290
      PI=3.14159265
      AMBDA=WAVELT/.3048006096
C-----------------------------------------------------------------------
C     CALCULATE PERMITTIVITY AND CONDUCTIVITY CONSTANTS
```

```
C-----------------------------------------------------------------------
      E1 = 62.16218883+23.56361954*AMBDA
      SIGMA = 21.08111081-(57.73381111*AMBDA)+(47.81338932*AMBDA**2)
      FSIG=(PT*(GT**2)*XNEIN)/(((4*PI)**3)*SL)
      FTAR=WAVELT**2.
C-----------------------------------------------------------------------
C     CALCULATE THE RADAR RECEIVER NOISE
C-----------------------------------------------------------------------
      RNOISE=C*TO*FN*BN
      DENOM=RNOISE
      PREALT = ALTEND
      BETA1 = (PI/2)-(RNGBGN/(RE+ALTBGN))
      BETA2 = (PI/2)-(RNGEND/(RE+ALTEND))
      GAMMA = (ALTBGN-ALTEND)/(BETA1-BETA2)
      STEP = (BETA2-BETA1)/(X(19)-X(20))
      ISTOP = X(19)
      START = ((ALTEND-H1)/6076.11549)+1.5
      IF (X(20) .GT. START) ISTART = X(20)
      IF (X(20) .LE. START) ISTART = START
      DO 300 I = ISTART,ISTOP
      H2 = RE+PREALT
      SIDE1 = (SINF(BETA2))*H2
      SIDE1 = SIDE1-(RE+H1)
      SIDE2 = (COSF(BETA2))*H2
      RT = ((SIDE1**2)+(SIDE2**2))**0.5
      RHORIZ = 1.068*(SQRTF(X(15)))*(SQRTF(H1)+SQRTF(H2-RE))*6076.11549
      IF (RT .GT. RHORIZ) GO TO 400
      R = RT*0.3048006096
      RR = R/1852.0035
      ALPHA = ALPHA1(1)+(ALPHA1(2)*LOGF(RR))
      ALPHA = ALPHA/(RR*1852.0035)
      ALPHA = (ALPHA/4.34)*(-1)
C-----------------------------------------------------------------------
C     CALCULATE THE SIGNAL RECEIVED FROM THE TARGET
C-----------------------------------------------------------------------
      SIGTAR=FSIG*FTAR*SIGT/(R**4)
      IF (ATTNTN.EQ.0) GO TO 30
      XNUM = SIGTAR*EXPF(2.*ALPHA*R)
      GO TO 40
   30 XNUM=SIGTAR
C-----------------------------------------------------------------------
C     CALCULATE THE MULTIPATH EFFECT
C-----------------------------------------------------------------------
   40 IF (XMPATH .EQ. 0.) GO TO 50
      CALL MPATH(RE,H1,H2,RT,AMBDA,E1,SIGMA,H,RPOLAR,DBDP)
C-----------------------------------------------------------------------
C     CALCULATE THE JAMMING SIGNAL STRENGTH
C-----------------------------------------------------------------------
   50 IF (XJAM.EQ.0) GO TO 80
      IF (TYPJAM .LT. .5) GO TO 60
      RJ = R
   60 IF (STBJAM .LT. .5) GO TO 61
      IF (STBJAM .LT. 1.5) GO TO 62
      IF (STBJAM .LT. 2.5) GO TO 63
   61 CALL SIDE (PJGJ,GT1,WAVELT,BN,PI,BJ,RJ,SIGJAM)
```

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      GO TO 70
   62 CALL MAIN (PJGJ,GT,WAVELT,BN,PI,BJ,RJ,SIGJAM)
      GO TO 70
   63 CALL BOTH (PJGJ,GT,GT1,WAVELT,BN,PI,BJ,RJ,SIGJAM)
   70 IF (ATTNTN .EQ. 0) GO TO 71
      SIGJAM = SIGJAM*EXPF(ALPHA*RJ)
   71 DENOM = DENOM+SIGJAM
C-----------------------------------------------------------------------
C     CALCULATE THE SURFACE CLUTTER EFFECT
C-----------------------------------------------------------------------
   80 IF (SURFCE.EQ.0) GO TO 120
      XRNG=5639.0398*(SQRTF(X(15)))*(SQRTF(H1))
      IF (RT.LE.XRNG) GO TO 90
      FACT2=0.
      GO TO 110
   90 FACT2=(PT*(GT**2)*(WAVELT)*BZ*CLT*TAU*SIGO)/
     1(2.*((4.*PT)**3))
      IF (ATTNTN.EQ.0) GO TO 100
      FACT2 = (FACT2*EXPF(2.*ALPHA*R))/(R**3)
      GO TO 110
  100 FACT2=FACT2/(R**3)
  110 DENOM=DENOM+FACT2
C-----------------------------------------------------------------------
C     CALCULATE THE WEATHER CLUTTER EFFECT
C-----------------------------------------------------------------------
  120 IF (WEATHR.EQ.0)  GO TO 145
      FACT3=(186.*PT*GT*CLT*TAU*(PI**4)*(RAIN**1.6))/
     1(128.*(WAVETH**2)*(10.**18))
      IF (ATTNTN.EQ.0) GO TO 130
      FACT3=FACT3*EXPF(2.*ALPHA*R)/(R**2)
      GO TO 140
  130 FACT3  = FACT3/(R**2)
  140 DENOM = DENOM+FACT3
  145 SGNS = XNUM/DENOM
      SGNS=DB(SGNS)
      DBDP = DBDP*2.
  150 SGNSDB(I)=SGNS+DBDP
      RNM(I) = R/1852.0035
      GO TO 200
 9000 PRINT 9010,RNM(I)
 9010 FORMAT (5X,*TARGET RANGE=*,E17.9)
 9011 PRINT 9020,SGNSDB(I)
 9020 FORMAT (5X,*TOTAL S/N RATIO=*,E17.9)
 9021 IF (XMPATH .EQ. 0.) GO TO 9061
 9022 PRINT 9030,SGNS,DBDP
 9030 FORMAT (5X,*S/N RATIO W/O MULTIPATH=*,E17.9,5X,*MULTIPATH EFFECT=*
     1,E17.9)
 9031 PRINT 9040,RT,R1,R2,DELTAR,ANGLE1,ANGLE2
 9040 FORMAT (5X,*RT=*,F10.2,5X,*R1=*,F10.2,5X,*R2=*,F10.2,5X,*DELTAR=*,
     1F10.2,5X,*ANGLE1=*,E17.9,5X,*ANGLE2=*,E17.9)
 9042 PRINT 9050,RRD,RHO,RV,D
 9050 FORMAT (5X,*MULTIPATH COEFF=*,E17.9,5X,*ROUGH SEA COEFF=*,E17.9/,5
     1X,*SMOOTH SEA COEFF=*,E17.9,5X,*DIVERGENCE=*,E17.9)
 9052 PRINT 9060,PHI,PHID,PHIV
 9060 FORMAT (5X,*TOTAL PHASE DIFF=*,E17.9,5X,*RANGE PHASE DIFF=*,E17.9,
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     15X,*REFLECTED PHASE DIFF=*,E17.9)
      GO TO 9063
 9061 PRINT 9062
 9062 FORMAT (5X,*MULTIPATH EFFECT NOT CONSIDERED*)
 9063 IF (XJAM .EQ. 0.) GO TO 9092
 9064 IF (ATTNTN .EQ. 1.) GO TO 9082
 9065 PRINT 9080,SIGJAM
 9080 FORMAT (5X,*UNATTENUATED JAMMING SIGNAL=*,E17.9)
 9081 GO TO 9101
 9082 PRINT 9090,SIGJAM
 9090 FORMAT (5X,*ATTENUATED JAMMING SIGNAL=*,E17.9)
 9091 GO TO 9101
 9092 PRINT 9100
 9100 FORMAT (5X,*NO JAMMING SIGNAL*)
 9101 IF (SURFCE .EQ. 0.) GO TO 9122
 9102 IF (ATTNTN .EQ. 1.) GO TO 9112
 9103 PRINT 9110,FACT2
 9110 FORMAT (5X,*UNATTENUATED SURFACE CLUTTER=*,E17.9)
 9111 GO TO 9131
 9112 PRINT 9120,FACT2
 9120 FORMAT (5X,*ATTENUATED SURFACE CLUTTER=*,E17.9)
 9121 GO TO 9131
 9122 PRINT 9130
 9130 FORMAT (5X,*SURFACE CLUTTER NOT CONSIDERED*)
 9131 IF (WEATHR .EQ. 0.) GO TO 9152
 9132 IF (ATTNTN .EQ. 1.) GO TO 9142
 9133 PRINT 9140,FACT3
 9140 FORMAT (5X,*UNATTENUATED WEATHER CLUTTER=*,E17.9//)
 9141 GO TO 200
 9142 PRINT 9150,FACT3
 9150 FORMAT (5X,*ATTENUATED WEATHER CLUTTER,*,E17.9//)
 9151 GO TO 200
 9152 PRINT 9160
 9160 FORMAT (5X,*WEATHER CLUTTER NOT CONSIDERED*//)
  200 BETA2 = BETA2-STEP
      PREALT = PREALT-(GAMMA*STEP)
      DENOM = RNOISE
  300 CONTINUE
      GO TO 600
  400 PRINT 500
  500 FORMAT (5X,*TARGET BEYOND RADAR HORIZON*)
  600 RETURN
      END
```

```
      SUBROUTINE MPATH(RE,H1,H2,RT,AMBDA,E1,SIGMA,H,RPOLAR,DBDP)
C-----------------------------------------------------------------------
C     SUBROUTINE TO DETERMINE THE MULTIPATH EFFECT
C-----------------------------------------------------------------------
      COMMON X(35),FNM(350),SGNSDB(350),TEMP(10),DELTAR,
     1R1,R2,ANGLE1,ANGLE2,PHI,PHID,PHIV,RRD,RHO,RV,D,ISTOP,PI
      COMPLEX CFNSQD,CFN,E,CFFCNT,BE
      HT = H2-RE
      FNUM=((RE+H1)**2)+((RE+HT)**2)-(RT**2)
      FDENOM=2*(RE+H1)*(RE+HT)
      ANS=FNUM/FDENOM
      THETA=ACOSF(ANS)
      XLEFT=0.
      RIGHT=THETA
      THETA1=THETA/2.
C-----------------------------------------------------------------------
C     ITERATIVE PROCESS TO CALCULATE ANGLE OF INCIDANCE/REFECTION
C-----------------------------------------------------------------------
      DO 30  I=1,31
      THETA2=THETA-THETA1
      CALL DIST(H1,THETA1,RE,R1)
      CALL DIST(HT,THETA2,RE,R2)
      RSULT1=((H1**2)+(2.*RE*H1)-(R1**2))/(2.*RE*R1)
      PSI1=ASINF(RSULT1)   $ ANGLE1=PSI1*(360./(2.*PI))
      RSULT2=((HT**2)+(2.*RE*HT)-(R2**2))/(2.*RE*R2)
      PSI2=ASINF(RSULT2)   $ ANGLE2=PSI2*(360./(2.*PI))
      IF (PSI1.GT.PSI2) GO TO 10
      RIGHT=THETA1
      GO TO 20
   10 XLEFT=THETA1
   20 THETA1=XLEFT+((RIGHT-XLEFT)/2.)
   30 CONTINUE
C-----------------------------------------------------------------------
C     CALCULATE PATH LENGTH DIFFERENCE
C-----------------------------------------------------------------------
      DELTAR=(R1+R2)-RT
C-----------------------------------------------------------------------
C     CALCULATE PHASE SHIFT DUE TO PATH LENGTH DIFFERENCE
C-----------------------------------------------------------------------
      PHID=(DELTAR*2.*PI)/AMBDA
C-----------------------------------------------------------------------
C     CALCULATE SIGNAL STRENGTH REDUCTION AND PHASE SHIFT CAUSED BY
C     REFLECTION
C-----------------------------------------------------------------------
      G=((PI*H*SINF(PSI1)/AMBDA)**2)
      RHO=EXPF(-8*G)
      CFNSQD=(E1*(1.,0.))-((0.,1.)*18.3*SIGMA*AMBDA)
      CFN=CSQRT(CFNSQD)
      E=SINF(PSI1)*(1.,0.)
      IF (RPOLAR.EQ.0) GO TO 40
      CFFCNT=(E-CFN)/(E+CFN)
      GO TO 50
   40 BE=(1.,0.)/CFN
      CFFCNT=(E-BE)/(E+BE)
   50 RV=CABS(CFFCNT)
```

```
      PHIV=CANG(CFFCNT)
C-----------------------------------------------------------------------
C     CALCULATE TOTAL PHASE SHIFT
C-----------------------------------------------------------------------
      PHI=PHID-PHIV
      W=(2.*R1*R2)/(RE*(R1+R2)*E)
      D=1./SQRTF(1.+W)
      RRD=RHO*RV*D
C-----------------------------------------------------------------------
C     CALCULATE MULTIPATH EFFECT
C-----------------------------------------------------------------------
      DELTAF=1.+(RRD**2)+(2.*RRD*COSF(PHI))
      DBDP=10.*ALOG10(DELTAF)
      RETURN
      END
```

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```
      SUBROUTINE DIST(XH,TH,RE,XR)
C-----------------------------------------------------------------------
C     SUBROUTINE TO CALCULATE DISTANCE FROM RADAR TO POINT OF REFLECTION
C     AND FROM POINT OF REFLECTION TO TARGET
C-----------------------------------------------------------------------
      IF (TH.GT..007) GO TO 10
      D=.5*(TH**2)
      GO TO 20
   10 D=1-COSF(TH)
   20 T=RE*(RE+XH)
      T=T*2.*D
      T=T+(XH**2)
      XR=SQRTF(T)
      RETURN
      END
```

```
      SUBROUTINE SIDE (PJGJ,GT1,WAVELT,BN,PI,BJ,RJ,SIGJAM)
C-----------------------------------------------------------------------------
C     CALCULATE SIDE-LOBE JAMMING SIGNAL
C-----------------------------------------------------------------------------
      IPJGJ = PJGJ
      NPJGJ = IPJGJ/10000
      SIGJAM = (NPJGJ*GT1*(WAVELT**2)*BN)/(((4.*PI)**2)*BJ*(RJ**2))
      RETURN
      END
```

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```
      SUBROUTINE MAIN (PJGJ,GT,WAVELT,BN,PI,BJ,RJ,SIGJAM)
C-----------------------------------------------------------------------
C     CALCULATE MAIN-LOBE JAMMING SIGNAL
C-----------------------------------------------------------------------
      IPJGJ = PJGJ
      NPJGJ = IPJGJ/10000
      MPJGJ = IPJGJ-(10000*NPJGJ)
      SIGJAM = (MPJGJ*GT*(WAVELT**2)*BN)/(((4.*PI)**2)*BJ*(RJ**2))
      RETURN
      END
```

```
      SUBROUTINE BOTH (PJGJ,GT,GT1,WAVELT,BN,PI,BJ,RJ,SIGJAM)
C---------------------------------------------------------------------------
C     CALCULATE SIDE AND MAIN-LOBE JAMMING SIGNAL
C---------------------------------------------------------------------------
      IPJGJ = PJGJ
      NPJGJ = IPJGJ/10000
      MPJGJ = IPJGJ-(10000*NPJGJ)
      SIG1 = (NPJGJ*GT1*(WAVELT**2)*BN)/(((4.*PI)**2)*BJ*(RJ**2))
      SIG2 = (MPJGJ*GT*(WAVELT**2)*BN)/(((4.*PI)**2)*BJ*(RJ**2))
      SIGJAM = SIG1+SIG2
      RETURN
      END
```

APPENDIX E

REFLECTED RAY PATH LENGTH CALCULATIONS

APPENDIX E

REFLECTED RAY PATH LENGTH CALCULATIONS

In the section on multipath effects, it was claimed that the technique used to determine the length of the reflected ray path calculated the point of incidence/reflection to within one inch for targets with a range up to 300 nautical miles. The portion of the radar detection model that calculates the reflected ray path length was converted to the APL computer language. This version is presented in annex E-1. Additional programming was inserted to determine the error in the point of reflection. Tables E-1 through E-4 present the results of various target altitudes, ranges, and flight profiles. The error between the calculated point of reflection and the actual point of reflection was determined to be less than one inch.

TABLE E-1

REFLECTED RAY PATH LENGTH CALCULATIONS

TARGET ALTITUDE AT THE BEGINNING OFF THE RUN = 300 FEET
TARGET ALTITUDE AT THE END OFF THE RUN = 300 FEET
TARGET RANGE AT THE BEGINNING OF THE RUN = 25 NAUTICAL MILES
TARGET RANGE AT THE END OF THE RUN = 0 NAUTICAL MILES
RADAR ANTENNA HEIGHT = 60 FEET

TARGET RANGE (NM)	R1 (FEET)	R2 (FEET)	DELTA RANGE (FEET)	ANGLE DIFFERENCE (DEG)	DISTANCE ERROR (INCH)
24.9	41136.3	110766.0	8.5E¯2	2.202682480E¯12	0._E0
23.9	38486.8	107339.3	1.7E¯2	7.389644451E¯13	0._E0
22.9	35920.2	103829.9	5.7E¯2	1.364242052E¯12	0._E0
21.9	33441.8	100232.3	1.3E¯1	1.961097950E¯12	0._E0
20.9	31056.1	96542.0	1.6E¯1	1.648459146E¯12	0._E0
19.9	28766.8	92755.2	1.4E¯1	6.622258297E¯12	0._E0
18.9	26576.8	88869.1	5.8E¯2	8.526512829E¯14	0._E0
17.9	24487.5	84882.3	9.7E¯2	2.557953848E¯12	0._E0
16.9	22499.4	80794.5	1.7E¯1	1.762145984E¯12	0._E0
15.9	20611.3	76606.5	1.9E¯1	1.705302565E¯13	0._E0
14.9	18821.2	72320.7	3.6E¯1	1.818989403E¯12	0._E0
13.9	17125.5	67940.2	2.0E¯1	3.296918293E¯12	0._E0
13.0	15520.0	63469.7	2.0E¯1	2.614797267E¯12	0._E0
12.0	13999.3	58914.4	2.5E¯1	3.069544618E¯12	0._E0
11.0	12557.6	54280.1	3.4E¯1	7.844391802E¯12	0._E0
10.0	11188.5	49573.5	6.9E¯1	4.774847184E¯12	0._E0
9.0	9885.3	44800.7	7.5E¯1	6.821210263E¯12	0._E0
8.0	8641.1	39968.8	6.5E¯1	3.979039320E¯12	0._E0
7.0	7449.1	35085.0	8.5E¯1	3.183231456E¯12	0._E0
6.0	6302.3	30155.8	8.8E¯1	9.777068044E¯12	0._E0
5.0	5194.1	25188.2	1.0E0	2.250999386E¯11	0._E0
4.0	4117.8	20189.5	1.7E0	6.593836587E¯12	0._E0
3.0	3066.6	15165.1	1.8E0	3.137756721E¯11	0._E0
2.0	2034.6	10123.2	3.3E0	1.728039933E¯11	0._E0
1.0	1015.5	5071.4	6.0E0	2.091837814E¯11	2.3E¯7

TABLE E-2

REFLECTED RAY PATH LENGTH CALCULATIONS

TARGET ALTITUDE AT THE BEGINNING OF THE RUN = 10,000 FEET
TARGET ALTITUDE AT THE END OF THE RUN = 10,000 FEET
TARGET RANGE AT THE BEGINNING OF THE RUN = 100 NAUTICAL MILES
TARGET RANGE AT THE END OF THE RUN = 75 NAUTICAL MILES
RADAR ANTENNA HEIGHT = 60 FEET

TARGET RANGE (NM)	R1 (FEET)	R2 (FEET)	DELTA RANGE (FEET)	ANGLE DIFFERENCE (DEG)	DISTANCE ERROR (INCH)
99.9	9720.5	597852.6	7.0E¯1	8.640199666E¯11	0._E0
98.9	9333.7	592165.6	7.3E¯1	5.798028723E¯12	0._E0
97.9	8970.3	586455.2	7.6E¯1	6.718892109E¯11	0._E0
96.9	8628.3	580723.4	8.1E¯1	9.447376214E¯11	0._E0
95.9	8306.1	574971.7	8.2E¯1	4.729372449E¯11	0._E0
94.9	8002.1	569202.0	8.5E¯1	8.98126018_E¯12	0._E0
93.9	7714.8	563415.5	8.8E¯1	1.090597834E¯9	0._E0
92.9	7443.1	557613.5	9.3E¯1	4.388311936E¯11	0._E0
91.9	7185.6	551797.3	9.8E¯1	1.534772309E¯10	0._E0
90.9	6941.4	545967.8	1.0E0	1.514308678E¯10	0._E0
89.9	6709.4	540126.0	1.0E0	1.205080479E¯10	0._E0
88.9	6488.8	534272.9	1.0E0	1.623448042E¯10	0._E0
87.9	6278.9	528409.2	1.1E0	1.557509676E¯10	0._E0
86.9	6078.7	522535.7	1.1E0	8.049028110E¯11	0._E0
85.9	5887.8	516653.0	1.1E0	6.821210263E¯12	0._E0
84.9	5705.4	510761.8	1.2E0	1.782609615E¯10	0._E0
83.9	5531.0	504862.6	1.2E0	1.914486347E¯10	0._E0
83.0	5364.1	498955.9	1.3E0	9.076757123E¯10	0._E0
82.0	5204.2	493042.3	1.3E0	1.218722900E¯10	0._E0
81.0	5050.8	487122.1	1.3E0	7.958078640E¯11	0._E0
80.0	4903.6	481195.8	1.4E0	9.958966984E¯11	0._E0
79.0	4762.2	475263.7	1.4E0	1.191438059E¯10	0._E0
78.0	4626.2	469326.3	1.5E0	2.185061021E¯10	0._E0
77.0	4495.3	463383.8	1.5E0	3.167315298E¯10	0._E0
76.0	4369.2	457436.5	1.6E0	1.177795638E 10	0._E0

TABLE E-3

REFLECTED RAY PATH LENGTH CALCULATIONS

TARGET ALTITUDE AT THE BEGINNING OF THE RUN = 75,000 FEET
TARGET ALTITUDE AT THE END OF THE RUN = 75,000 FEET
TARGET RANGE AT THE BEGINNING OF THE RUN = 100 NAUTICAL MILES
TARGET RANGE AT THE END OF THE RUN = 75 NAUTICAL MILES
RADAR ANTENNA HEIGHT = 60 FEET

TARGET RANGE (NM)	*R1 (FEET)*	*R2 (FEET)*	*DELTA RANGE (FEET)*	*ANGLE DIFFERENCE (DEG)*	*DISTANCE ERROR (INCH)*
100.6	535.7	610871.7	1.3E1	1.121043169E¯8	4.0E¯6
99.6	529.4	604856.8	1.3E1	3.754394128E¯9	1.3E¯6
98.6	523.2	598842.7	1.3E1	1.424814399E¯8	5.2E¯6
97.6	517.0	592829.6	1.3E1	2.213710104E¯9	8.3E¯7
96.6	510.8	586817.4	1.4E1	4.549292498E¯9	1.5E¯6
95.6	504.6	580806.2	1.4E1	7.870767149E¯9	2.8E¯6
94.6	498.5	574796.0	1.4E1	3.170498530E¯9	1.1E¯6
93.6	492.4	568786.9	1.4E1	3.153218131E¯8	1.1E¯5
92.6	486.4	562778.8	1.4E1	1.006083039E¯8	3.5E¯6
91.7	480.3	556771.9	1.4E1	1.256194082E¯8	4.5E¯6
90.7	474.3	550766.2	1.5E1	9.014911483E¯9	3.2E¯6
89.7	468.4	544761.6	1.5E1	3.218519850E¯8	1.1E¯5
88.7	462.4	538758.3	1.5E1	3.432433004E¯8	1.2E¯5
87.7	456.5	532756.3	1.5E1	2.300293999E¯8	8.2E¯6
86.7	450.7	526755.6	1.5E1	1.511580194E¯8	5.4E¯6
85.7	444.8	520756.3	1.6E1	7.777998689E¯9	2.8E¯6
84.7	439.0	514758.4	1.6E1	3.105014911E¯8	1.1E¯5
83.8	433.2	508762.0	1.6E1	7.305061444E¯9	2.6E¯6
82.8	427.4	502767.2	1.6E1	3.342938725E¯8	1.1E¯5
81.8	421.7	496773.9	1.7E1	2.122033038E¯8	7.6E¯6
80.8	416.0	490782.3	1.7E1	1.455555320E¯8	5.3E¯6
79.8	410.3	484792.4	1.7E1	2.656088327E¯8	9.5E¯6
78.8	404.6	478804.4	1.7E1	1.958323991E¯8	7.0E¯6
77.8	399.0	472818.1	1.8E1	7.490598363E¯9	2.7E¯6
76.8	393.4	466833.8	1.8E1	4.152389010E¯8	1.4E¯5

TABLE E-4

REFLECTED RAY PATH LENGTH CALCULATIONS

TARGET ALTITUDE AT THE BEGINNING OF THE RUN = 75,000 FEET
TARGET ALTITUDE AT THE END OF THE RUN = 75,000 FEET
TARGET RANGE AT THE BEGINNING OF THE RUN = 25 NAUTICAL MILES
TARGET RANGE AT THE END OF THE RUN = 1 NAUTICAL MILE
RADAR ANTENNA HEIGHT = 60 FEET

TARGET RANGE (NM)	R1 (FEET)	R2 (FEET)	DELTA RANGE (FEET)	ANGLE DIFFERENCE (DEG)	DISTANCE ERROR (INCH)
27.8	136.0	169116.7	5.3E1	1.356238499E¯8	4.8E¯6
26.9	131.6	163704.6	5.4E1	3.508466761E¯8	1.2E¯5
26.0	127.2	158339.6	5.6E1	5.410402081E¯8	1.9E¯5
25.1	122.9	153026.8	5.8E1	5.935726221E¯8	2.1E¯5
24.3	118.6	147771.8	6.0E1	5.321635399E¯8	1.9E¯5
23.4	114.4	142581.0	6.2E1	7.172639016E¯8	2.5E¯5
22.6	110.3	137461.4	6.5E1	1.308508217E¯7	4.7E¯5
21.8	106.2	132421.7	6.7E1	2.437445800E¯8	8.7E¯6
20.9	102.2	127471.1	7.0E1	1.167791197E¯7	4.2E¯5
20.1	98.3	122620.5	7.3E1	1.156149664E¯7	4.1E¯5
19.4	94.4	117882.2	7.6E1	1.378066372E¯8	4.9E¯6
18.6	90.7	113270.2	7.9E1	7.436028681E¯8	2.6E¯5
17.9	87.1	108800.7	8.2E1	8.221832104E¯9	2.9E¯6
17.1	83.6	104491.9	8.5E1	6.303889676E¯8	2.2E¯5
16.5	80.3	100364.6	8.9E1	2.908927854E¯8	1.0E¯5
15.8	77.2	96442.1	9.3E1	2.823071554E¯9	1.0E¯6
15.2	74.2	92750.4	9.6E1	1.290463842E¯7	4.6E¯5
14.6	71.4	89318.1	1.0E2	8.802453521E¯8	3.1E¯5
14.1	68.9	86176.1	1.0E2	1.052685547E¯7	3.7E¯5
13.7	66.7	83357.1	1.0E2	3.492459654E¯8	1.2E¯5
13.3	64.7	80895.3	1.1E2	8.806819096E¯8	3.1E¯5
12.9	63.0	78823.7	1.1E2	8.358620107E¯8	3.0E¯5
12.6	61.7	77174.0	1.1E2	6.443588063E¯8	2.3E¯5
12.4	60.7	75974.0	1.1E2	1.725857146E¯8	6.2E¯6
12.3	60.1	75244.8	1.1E2	1.030275598E¯8	3.6E¯6

ANNEX E-1

REFLECTED RAY PATH LENGTH PROGRAM

```
    ∇ ERROR
[1]    'TARGET          R1          R2          DELTA         ANGLE            DISTANCE
[2]    'RANGE                                   RANGE       DIFFERENCE          ERROR'
[3]    ' (NM)        (FEET)      (FEET)        (FEET)         (DEG)            (INCH)'
[4]    PI←3.14159265
[5]    ER←20891199×X14
[6]    ALTBGN←X16
[7]    ALTEND←X17
[8]    RNGBGN←X18×6076.11549
[9].   RNGEND←X19×6076.11549
[10]   H1←X31
[11]   PREALT←ALTBGN
[12]   BETA1←(PI÷2)-(RNGBGN÷(ER+ALTBGN))
[13]   BETA2←(PI÷2)-(RNGEND÷(ER+ALTEND))
[14]   GAMMA←(ALTBGN-ALTEND)÷(BETA1-BETA2)
[15]   STEP←(BETA2-BETA1)÷(X18-X19)
[16]  AC:H2←ER+PREALT
[17]   SIDE1←(1○(BETA1))×H2
[18]   SIDE1←SIDE1-(ER+H1)
[19]   SIDE2←(2○(BETA1))×H2
[20]   RT←((SIDE1*2)+(SIDE2*2))*0.5
[21]   HT←H2-ER
[22]   FNUM←((ER+H1)*2)+((ER+HT)*2)-(RT*2)
[23]   FDENOM←2×(ER+H1)×(ER+HT)
[24]   ANS←FNUM÷FDENOM
[25]   THETA←¯2○ANS
[26]   LEFT←0
[27]   RIGHT←THETA
[28]   THETA1←THETA÷2
[29]   I←1
[30]  BB:THETA2←THETA-THETA1
[31]   R1←H1 DISTANCE THETA1
[32]   R2←HT DISTANCE THETA2
[33]   RSULT1←(H1*2)+(2×ER×H1)-(R1*2)
[34]   RSULT1←RSULT1÷(2×ER×R1)
[35]   PSI1←¯1○RSULT1
[36]   RSULT2←(HT*2)+(2×ER×HT)-(R2*2)
[37]   RSULT2←RSULT2÷(2×ER×R2)
[38]   PSI2←¯1○RSULT2
[39]   →BC×⍳PSI1>PSI2
[40]   RIGHT←THETA1
[41]   →BD
[42]  BC:LEFT←THETA1
[43]  BD:THETA1←LEFT+((RIGHT-LEFT)÷2)
[44]   I←I+1
[45]   →BB×⍳I≤32
[46]   DELTAR←(R1+R2)-RT
[47]   ANGLE1←PSI1×(360÷(2×PI))
[48]   ANGLE2←PSI2×(360÷(2×PI))
[49]   DIFF←|(PSI1-PSI2)
[50]   →ZA×⍳PSI1>PSI2
[51]   NEWPSI1←PSI1+(DIFF÷2)
```

```
[52]    →ZB
[53]   ZA:NEWPSI1←PSI1-(DIFF÷2)
[54]   ZB:MISS←|(((2○PSI1)×R1×12)-((2○NEWPSI1)×R1×12))
[55]    K1←(RT÷6076.11549)⍕6 3 2 0
[56]    K2←R1⍕13 7 2 0
[57]    K3←R2⍕13 7 2 0
[58]    K4←DELTAR⍕11 1 2 3
[59]    K5←DIFF⍕18 1 10 3
[60]    K6←MISS⍕12 2 2 3
[61]    (K1),(K2),(K3),(K4),(K5),(K6)
[62]    PREALT←PREALT+(GAMMA×STEP)
[63]    BETA1←BETA1+STEP
[64]    END←(H1+ER)+RT-H2
[65]    →0×⍳END≤0
[66]    →0×⍳BETA1≥BETA2
[67]    →AC
[68]    DELTAR←(R1+R2)-RT
      ∇


      ∇ R←FDH DISTANCE FDTH
[1]     →GR×⍳FDTH>0.007
[2]     FDD←0.5×(FDTH*2)
[3]     →LN
[4]    GR:FDD←1-(2○FDTH)
[5]    LN:FDT←ER×(ER+FDH)
[6]     FDT←FDT×2×FDD
[7]     FDT←FDT+(FDH*2)
[8]     R←FDT*0.5
      ∇
```